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REVIEW OF CONVENTIONAL TACTICAL RADIO DIRECTION FINDING SYSTEMS

by

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ABSTRACT

This report discusses land based conventional tactical radio direction finding systems used in determining the direction of origin of narrowband (100 kHz or less) radio signals (AM, FM, CW, and SSB) in the 30 to 1000 MHz frequency band. These systems are examined from both the theoretical and practical points of view. Examples of actual systems and the problems encountered (and solutions where appropriate) under operational conditions are also given. Finally manufacturers specifications and how they relate to actual system operation and systems comparisons are also discussed.

RESUME

Ce rapport traite de systèmes tactiques, terrestres et conventionnels pour la détermination de la direction d'arrivée d'émission radio (AM, FM, tonalité et BLU) à faible bande passante (100 KHz ou moins) dans une bande de fréquences allant de 30 à 1000 MHz. Les aspect théoriques et pratiques de ces systèmes sont revus et on donne des exemples de systèmes réels ainsi que des exemples de problèmes (et, si possible, de solutions) qui surviennent en cours d'opération. On discute des spécifications des manufacturieurs et de la façon dont elles décrivent l'opération réelle des systèmes et on fait, de plus, une comparison de systèmes.

EXECUTIVE SUMMARY

This report reviews the performance of conventional landbased tactical VHF/UHF radio direction finding systems. This work was carried out to develop the necessary expertise for technical advice in support of current and future Canadian Forces direction finding systems, and the necessary background for research and development on advanced direction finding systems. Additionally, since at the time of writing this report there were no readily available books appropriate to the subject, this report seeks to help remedy the situation.

The systems discussed are used in determining the direction of origin of narrowband (100 kHz or less) radio signals (AM, FM, DW, and SSB) in the 30 to 1000 MHz frequency band. Three different types of systems are currently used which are called:

a) Watson-Watt,
b) pseudo-Doppler, and
c) phase interferometer.

These systems are conventional in the sense that they have reached a mature state of the development.

The Watson-Watt system works by using two directional antennas to measure the magnitude of the radio signal along two orthogonal baselines. These values are compared to the output of an omni-directional antenna to determine their sign (i.e. "+" or "-"). The signed values are then used as the arguments of the arc tangent function for computing the signal bearing.

There are several hardware implementations of this system which include three channel receiver systems (one channel for each antenna output) and single channel systems where the antenna outputs are combined into one receiver channel. The directional antennas used are either two of four element Adcock antennas. The omni-directional antenna may be a single dipole positioned at the center of the antenna array, or the summation of the outputs from the elements of the directional antennas.

In the pseudo-Doppler system, each antenna in a circular array is sampled sequentially to simulate the effect of a rotating antenna. This modulates the intercepted signal and the phase of this modulation can be used to determine the direction of origin of the signal.

There are two common implementations of this system. In the single channel system antennas are sequentially connected to the receiver to be demodulated. In the dual channel system a second channel is added which is connected to an omni-directional antenna positioned in the center of the antenna array. Mixing the two channels removes the effects of transmitter modulation but not the effect of the modulation due to switching antennas.

In the phase interferometer the phase difference information determined from measurements between spatially separated antennas is used to determine the direction of origin of the signal.

Implementations of this system include systems with a single receiver for each antenna, dual channel systems where pairs of antennas are measured sequentially, and single channel systems which are similar to the dual channel systems except the outputs from pairs of antennas are combined to preserve the phase information but require only one receiver channel.

There are a number of factors which reduce the accuracy of conventional direction finding systems under actual operational conditions. Multipath is a major problem and can cause errors on the order of several degrees in the bearing estimates [11]. Raising the height of the antenna array and increasing the diameter of the antenna array will (at least theoretically) reduce the effects of multipath. However these solutions tend to conflict with tactical requirements.

Co-channel interference can cause the bearing to vary rapidly. If the signal of interest is the strongest, averaging techniques can be used to determine its bearing. In a Watson-Watt system using a CRT display driven by the directional antenna outputs, a skilled operator may be able to determine the direction of the various signals being intercepted.

Equipment is a source of bearing errors, most notably in the antennas where mutual coupling between elements or interaction with the local environment can corrupt the antenna patterns from their expected response. Calibration techniques can significantly reduce some of these effects to the point that manufacturers make claims of equipment accuracies of 1 degree rms or less.

Noise, both equipment generated and environmental, effects the stability of the bearing measurement. Typically these are zero-mean processes so that averaging can reduce the variations in bearing to suitable levels. Significant errors can occur if the signal to noise ratio drops below about 10 dB.

In reviewing equipment manufacturers published specifications for direction finding systems, its was determined that it was not possible to compare systems in any meaningful sense. The major problem is that there is insufficient information provided on how the various specifications were obtained which is critical if effective comparisons are to be made.

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1.0 INTRODUCTION

This report reviews the performance of conventional landbased tactical VHF/UHF radio direction finding systems. This work was carried out to develop the necessary expertise for technical advice in support of current and future Canadian Forces direction finding systems, and the necessary background for research and development on advanced direction finding systems. Additionally, since at the time of writing this report there were no readily available books appropriate to the subject, this report seeks to help remedy the situation.

The systems discussed are used in determining the direction of origin of narrowband (100 kHz or less) radio signals (AM, FM, DW, and SSB) in the 30 to 1000 MHz frequency band. In this report, these systems are referred to simply as conventional direction finding (CDF) systems.

There are several tactical requirements for CDF systems which include:

a) Accuracy - As accurate as possible. In practice the best operational accuracy achieved by conventional DF systems has been on the order of a few degrees (too inaccurate for targeting purposes).

b) Automation - Once the system has been tasked to measure a signal bearing, the bearing should be determined automatically within a few seconds.

c) Mobility - Man-portable or vehicle mounted.

d) Short set up time - 10 to 20 minutes is the longest time a CDF system would want to remain at any site; anything longer reduces the survivability of the system. Consequently the set up time is constrained to be somewhat less than this in order that there is enough time for signal bearing measurements to be taken.

e) Robustness - Ruggedized to withstand the rigors of a military environment.

The first requirement, accuracy, is the main focus of this report. The fundamental limitations in accuracy imposed by nature as a function of the various techniques and implementations are discussed in some detail. Technological difficulties are also discussed as well as various measurement criteria used to describe system performance.

The second requirement, automation, constrains CDF systems to fixed antenna arrays. Direction finding techniques that require the antenna to be moved or rotated to determine the direction of arrival of the signal, are too slow for modern tactical purposes.

The final three requirements (mobility, short set-up time, and (robustness) limit CDF systems to being small and light enough to be carried by man or vehicle, simple to set up, and reliable.

Although many different types of radio direction finding systems exist, there are only three basic types of CDF systems currently used which meet these tactical requirements. These systems are:

a) Watson-Watt,
b) pseudo-Doppler, and
c) phase interferometer.

These systems are conventional in the sense that they have reached a mature state of development. For example, the Watson-Watt system was first proposed in 1926 [1], the pseudo-Doppler system in 1947 [2], and the phase interferometer system around 1961 [3]. All three systems were originally developed for direction finding in the HF frequency band, then later modified for operation at VHF and UHF frequencies.

2.0 THEORY OF OPERATION

The operation of CDF systems can be broken down in terms of three basic subsystems: the sensor system, the signal processor, and the display. Each of these subsystems is discussed in the following subsections.

In discussing the theoretical aspects of the operating principles of CDF systems, several assumptions are implicit (unless otherwise indicated):

1. The signal follows a single, direct, unobstructed path from the transmitter to the CDF system;
2. There are no interfering signals;
3. The signal wavefront is planar;
4. The angle of arrival of the signal in elevation is 0 degrees;
5. The signal is vertically polarized;
6. The signal is CW;
7. The measurement equipment is perfect;
8. Noise is absent.

The problems with real world systems when these assumptions break down and the solutions to these problems will be discussed in a later section.

To simplify discussion, a number of terms and conventions have been used throughout the rest of this report. The term "channel" is used to describe a signal path through the CDF system. For example, two signals occupying the same channel, share the same circuitry, but not necessarily the same frequency band.

The term "receiver front end" is used to describe the first input stage(s) of the receiver which shift the radio frequency (RF) signal to an intermediate frequency (IF), amplify it, and pass it through a bandpass filter. The bandwidth of the filter controls the receiver bandwidth.

Phase delays introduced by equipment components are assumed to be equal in all signal paths. Under this assumption, phase delays have no effect on CDF system operation, except where stated otherwise. Amplitude gains and losses are also assumed to be equal in all signal paths.

In the text that follows all angular measurements are expressed in degrees where the convention -180 to +180 degrees has also been adopted. In equations, however, the corresponding radian measure is used.

The arc tangent function used in the form

$$\phi = \text{arcTan}(Y/X)$$

throughout the discussion uses the signs of X and Y ("+" or "-") to correctly determine the quadrant of ϕ.

In the mathematical derivations that follow, the RF signal is assumed to generate a voltage in a matched dipole antenna of the form

$$S(t) = Vd\ \text{Sin}(\omega t + \gamma) \quad \text{Volts}$$

where the parameters of the equation are defined in the following paragraph. The phase angle γ is defined to be 0 degrees if the dipole is located at the geometric center of the antenna array of which it is a part.

Finally, a number of parameters are used repeatedly throughout this section. They are defined here as:

- t - time (seconds),
- ω - signal frequency (radians/second),
- λ - signal wavelength (meters),
- ϕ - true signal bearing in azimuth referenced to true North (radians),
- ϕc - bearing computed by the CDF system (radians),
- d - distance between a pair of antennas (meters),
- Vd - maximum voltage induced in a matched dipole antenna (Volts),
- γ - signal phase (radians).

2.1 The Sensor System

The sensor system electrically couples the CDF system to the radio signal environment. It consists of an array of two or more antennas which supply the appropriate signal information to the signal processor. There are essentially two different types of antennas used in the sensor system: phase measuring, and directional.

2.1.1 Phase Measuring Antennas

The vertical dipole antenna is used for making phase measurements. The ideal voltage gain pattern (in azimuth) of this antenna (shown in Figure 1a) is omni-directional, making the antenna equally sensitive to signals arriving from any direction.

Phase measurements are made indirectly. The dipole antenna measures the instantaneous amplitude of a signal at a specific point in space. The voltage generated in the antenna is given by the equation

$$V(t) = Vd \, Sin(\omega t + \gamma) \quad Volts. \tag{1}$$

By comparing the antenna voltage to a second dipole antenna voltage, the relative phase angles between the two antennas can be determined. In CDF antenna arrays where one antenna is used as a reference (for phase comparison purposes), this antenna is known as a "sense" antenna.

2.1.2 Directional Antennas

The ideal voltage gain pattern (in azimuth) of a directional antenna (shown in Figure 1b) used for the Watson-Watt system is given by the equation

$$Gain = Gm \, Cos(\phi), \tag{2}$$

where Gm is the maximum gain of the antenna. Due to the cosine form of the gain equation, this voltage gain pattern is often called the cosine pattern. It is apparent that, unlike the omni-directional phase antenna, the voltage gain of this antenna is highly dependent on the direction of arrival of the signal.

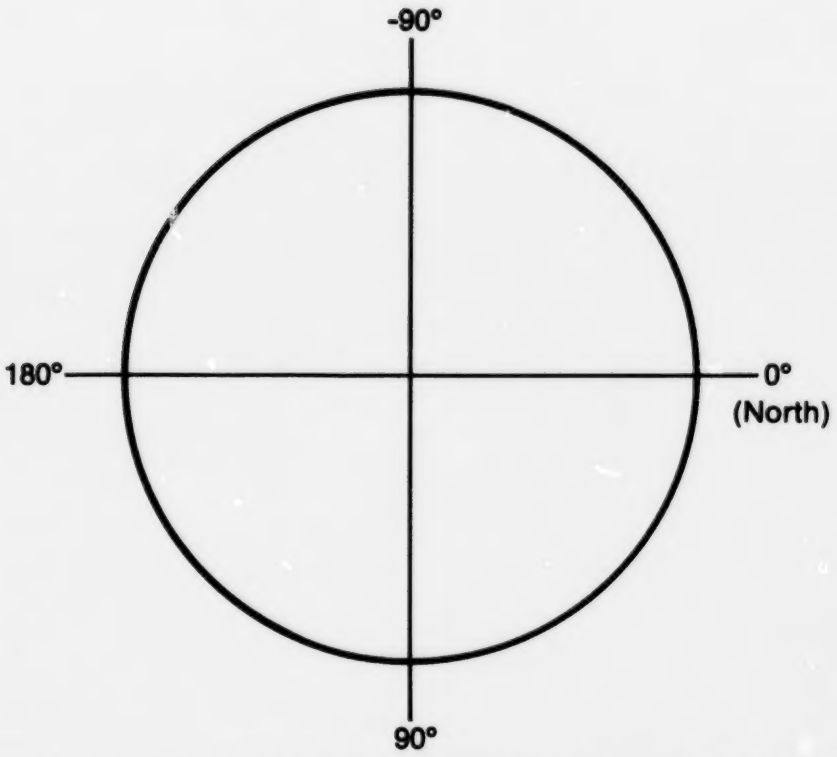
Real world directional antennas for CDF systems are constructed from two or more dipole elements. The actual voltage gain patterns are not true cosine patterns, but rather, approximations of it. Since deviations from the true cosine pattern result in errors in the bearing measurements, design of real world antenna arrays tries to minimize the cosine deviations.

2.1.2.1 2-Element Adcock Antennas

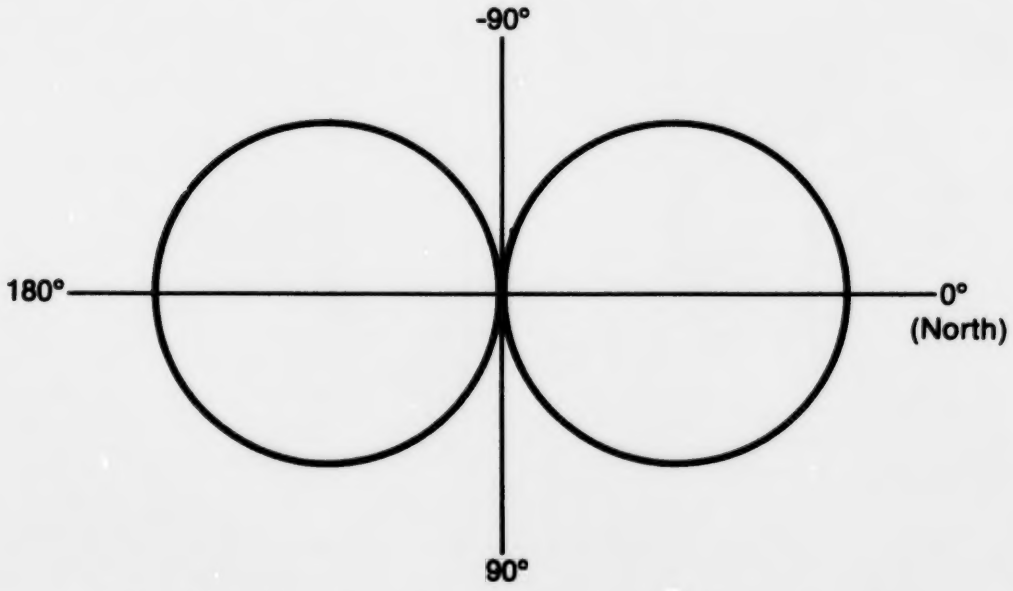
The most commonly used directional antenna is the 2-element Adcock antenna shown in Figure 2a. The output from this antenna is the difference between the output voltages of two spatially separated dipole elements. The voltage gain is described by the equation

$$Gain = 2 \, Gd \, Sin(\pi \, d/\lambda \, Cos(\phi)), \tag{3}$$

where Gd is the gain of a single dipole element.

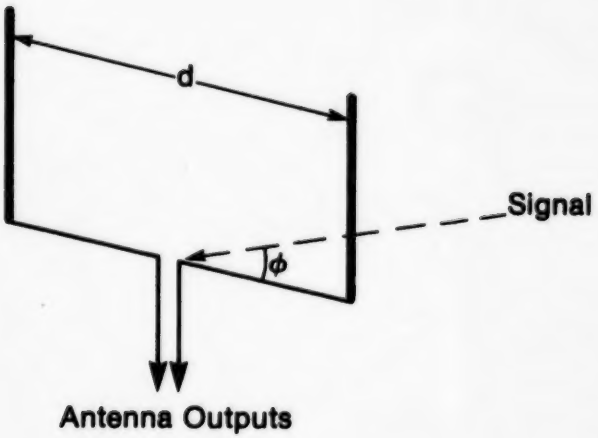


(a) Ideal Phase Sensor Voltage Gain Characteristic

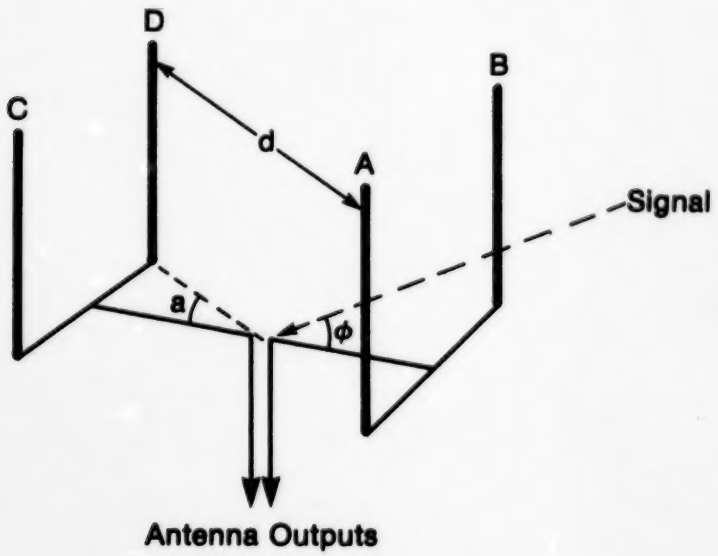


(b) Ideal Direction Antenna Voltage Gain Characteristic

FIGURE 1

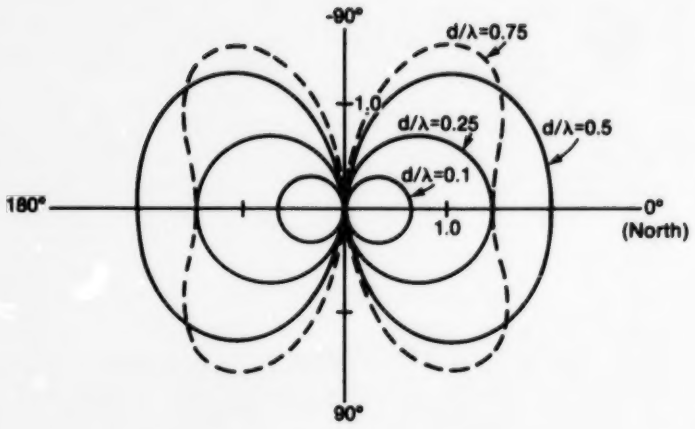


(a) 2-Element Adcock Antenna

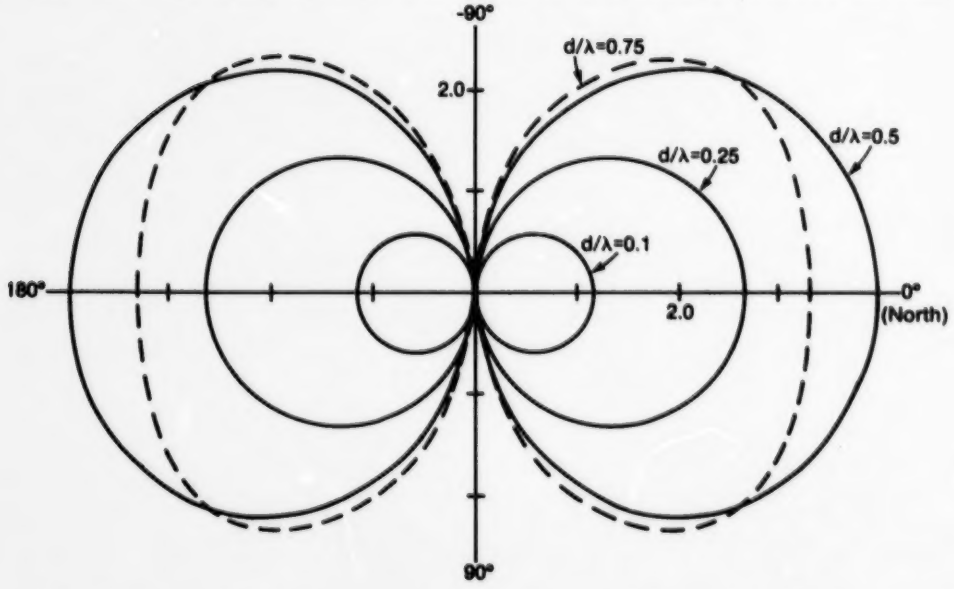


(b) 4-Element Adcock Antenna.

FIGURE 2



(a) Voltage Gain Characteristics for a 2-Element Adcock Antenna



(b) Voltage Gain Characteristics for a 4-Element Adcock Antenna

FIGURE 3

Figure 3a shows the change in gain pattern as the ratio of d/λ is varied. As d/λ approaches zero, Equation (3) approaches the ideal cosine form of the equation

$$\text{Gain} = 2Gd\ (\pi d/X)\ \text{Cos}(\phi) \qquad (4)$$

At values of d/λ greater than 1/4, the gain pattern begins to depart significantly from the shape of the ideal cosine pattern. In typical CDF systems, the maximum ratio of d/λ is restricted to 1/4 to minimize the errors in computed bearing caused by the deviation of the gain pattern from the ideal.

2.1.2.2 4-Element Adcock Antennas

A more complex version of the Adcock antenna is shown in Figure 2b. This antenna is similar to the 2-element antenna version except each antenna element has been replaced by a split pair of elements. The output is the difference in voltage between two summed pairs of elements (A+B and C+D) and this results in the voltage gain equation given by

$$\text{Gain} = 2\ Gd\ [\text{Sin}(\text{Cos}(\phi-a)\ \pi\ d/\lambda) + \text{Sin}(\text{Cos}(\phi+a)\ \pi\ d/\lambda)] \qquad (5)$$

where "a" is the half angle between summed antenna pairs and is generally a value between 22.5 and 27.5 degrees.

Figure 3b shows the change in gain pattern as the ratio of d/λ is varied. As d/λ approaches zero, Equation (5) approaches the ideal cosine form given by

$$\text{Gain} = 4Gd\ (\pi d/\lambda)\ \text{Cos}(a)\ \text{Cos}(\phi) \qquad (6)$$

Although not immediately obvious from the gain patterns shown in Figure 3, it will be shown later that the 4-element Adcock antenna has a much superior gain pattern than the 2-element antenna, and can be used at ratios of d/λ approaching 1.0 or more (compared to a ratio of 0.25 for the 2-element antenna).

2.2 Basic Signal Processors

Signal processing can be regarded as a three step process: frequency down conversion, demodulation, and bearing computation. A receiver down converts and amplifies an RF signal to a fixed intermediate frequency (IF). The demodulator, which may be part of the receiver, or in a separate unit, converts the signal from IF to a form suitable for the bearing processor which computes the bearing.

In some systems, the demodulated input signal to the bearing processor is not suitable for audio purposes (i.e. can not be used by the CDF operator to listen to the intercepted signal). If the demodulator used for the bearing processor is separate from the receiver, the receiver demodulator can be used to convert the signal to audio, otherwise a separate receiver may be required for this purpose.

There are three basic types of CDF systems: Watson-Watt, pseudo-Doppler, and phase interferometer. The signal processing requirements of each of these systems are different.

2.2.1 Watson-Watt System

The Watson-Watt system works by measuring the magnitude of the signal vector along two orthogonal axes. These quantities are then used as the arguments of the arctangent function to compute the signal bearing.

A block diagram of a Watson-Watt system is shown in Figure 4. The magnitudes of the two orthogonal signal vector components are measured using two perpendicularly oriented directional antennas. These antennas are required to have cosine gain patterns, so at VHF/UHF frequencies, Adcock antennas are used. Mathematically, the output signals from these antennas can be expressed as

$$X(t) = Va\ Cos(\phi)\ Cos(\omega t)\ Volts, \tag{7}$$

and

$$Y(t) = Va\ Sin(\phi)\ Cos(\omega t)\ Volts, \tag{8}$$

where Va is the maximum antenna output expressed in Volts. Note that the Cosine approximations (Equations (4) or (6)) for Adcock antennas have been used here.

After conversion of the RF signal to IF by the receiver, the signals are passed to a synchronous demodulator. In the demodulator, the mixer multiplies the reference signal with each of the two input signals X(t) and Y(t). The reference signal can be described mathematically as

$$R(t) = Vr\ Cos(\omega t)\ Volts \tag{9}$$

where Vr is the maximum voltage expressed in Volts. The low pass filter removes any high frequency components, and the resultant outputs are then given by

$$X = Vo\ Cos(\phi)\quad Volts \tag{10}$$

and

$$Y = Vo\ Sin(\phi)\quad Volts \tag{11}$$

where Vo is the maximum voltage expressed in Volts. The quantities X and Y are then used to compute the bearing angle using the equation

$$\phi c = \text{arcTan}(Y/X) \qquad (12)$$

The solution to ϕc is unique only if the reference is derived from a signal whose phase is independent of the signal bearing. This can be done in one of two ways. In the first method, the output from a dipole sense antenna, positioned at the geometric centre of the array, is utilized. The sense output from this antenna can be expressed mathematically as

$$Se(t) = Vs \, \text{Sin}(\omega t) \quad \text{Volts} \qquad (13)$$

where Vs represents the maximum signal magnitude expressed in volts. In the second method, the outputs from each dipole of the Adcock antennas are summed to give the sense output given as

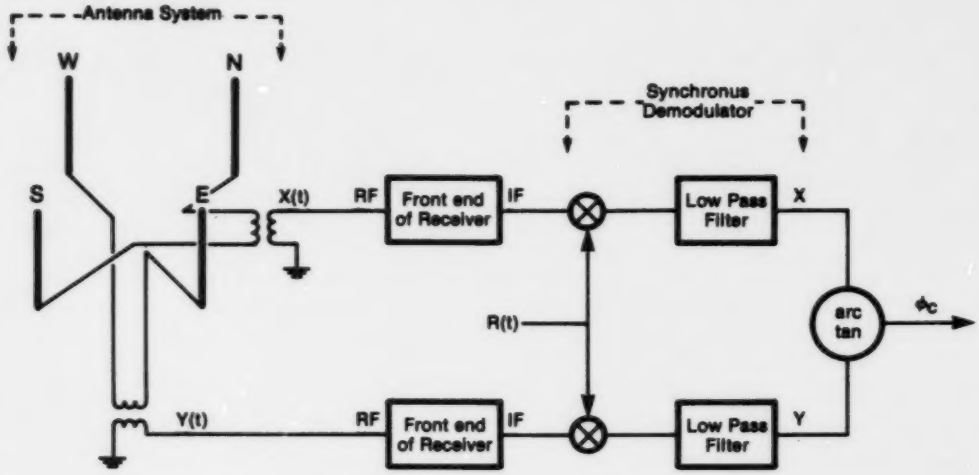
$$Se(t) = Vs' \, \text{Sin}(\omega t) \quad \text{Volts} \qquad (14)$$

In this case, the magnitude of Vs' has some dependence on the signal bearing, but is always non-zero and positive (no phase dependency) as long as the diameter of the antenna array does not exceed 0.7 of a wavelength. In either case, the sense signal is amplified and phase shifted by +90 degrees to give the required reference signal

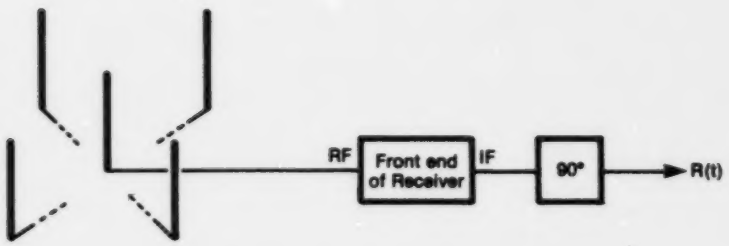
$$R(t) = Vr \, \text{Cos}(\omega t) \quad \text{Volts} \qquad (15)$$

2.2.2 The Pseudo-Doppler System

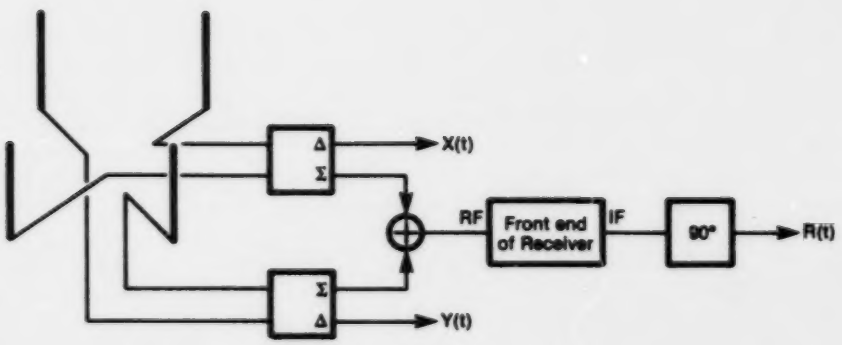
In the single channel pseudo-Doppler (or quasi-Doppler) system, omni-directional antennas are arranged in a circle with constant spacing. Each antenna is sampled sequentially to simulate the effect of a single antenna being rotated in a circle (called the simulated antenna here), the effect of which is to phase modulate the signal at a frequency identical to the rotation frequency (typically on the order of hundreds of hertz). A vector drawn from the center of the array to the simulated antenna aligns directly with the signal source when the instantaneous phase angle of the modulating waveform is 180 degrees (using a sine wave convention).



(a) Watson-Watt System Block Diagram



(b) Generation of a Reference Signal - Method 1



(c) Generation of a Reference Signal - Method 2

FIGURE 4

A block diagram of a pseudo-Doppler system is shown in Figure 5. The sensor system consists of a circular array of dipole antennas connected to an antenna controller. The controller sequentially connects one antenna at a time, to the receiver input. Adjacent antennas are spaced less than one half a wavelength apart to avoid ambiguities in the phase measurements.

The receiver converts the RF signal to an intermediate frequency suitable for the demodulator. The output of the demodulator is a voltage related to the input frequency of the signal, given by

$$Vo = k\,(Fs - Fc) \quad \text{Volts} \tag{16}$$

where:

Vo - output voltage of the demodulator,
k - gain of demodulator,
Fs - input signal frequency, and
Fc - carrier frequency.

Since there are various standard FM demodulators currently in use, and the internal operations of the demodulator are not important to this discussion, the specifics of the demodulator are not discussed here.

If a rotating antenna was used in the sensor system, the output of the demodulator would vary smoothly as shown in Figure 6a. However, since the effect of rotation is simulated by sequentially sampling the outputs of a discrete number of antennas, the demodulator output is actually a series of spikes (Figure 6b). These spikes occur during transitions from one antenna to another resulting in a sudden change in signal phase. Since frequency is a measure of the rate of change of the instantaneous signal phase, this sudden change in phase appears as a sudden apparent change in frequency. A bandpass filter centered at the antenna rotation frequency, smooths out the spikes.

From this smoothed waveform, the DF processor determines the negative zero crossing of the signal. The DF processor also keeps track of the angular position of the simulated rotating antenna (which is assumed to be smoothly varying). The signal bearing angle is the angular position of the simulated antenna with respect to the center of the antenna array at the time of the negative zero crossing. If any phase delays are added by the equipment during signal processing, this results in a fixed offset that must be subtracted from the measured bearing.

A variation of the single channel pseudo-Doppler system described above is the differential pseudo-Doppler system shown in Figure 7. This system employs a sense antenna (dipole antenna) located at the center of the array. The two antenna system outputs (the sampled antenna output and the sense antenna output) are converted to the intermediate frequencies f1 and f2. The outputs are mixed and then filtered to remove the high frequency components f1 + f2. The rest of the processing from the demodulator onwards is the same as described previously. The advantage of this system is the removal of frequency variations in the RF signal that are not caused by the Doppler rotation. This is important when signals other than CW are considered.

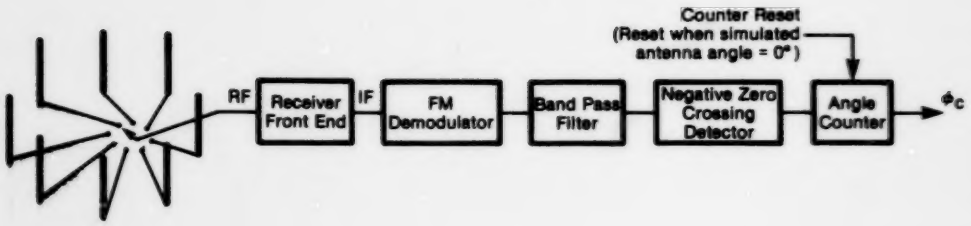
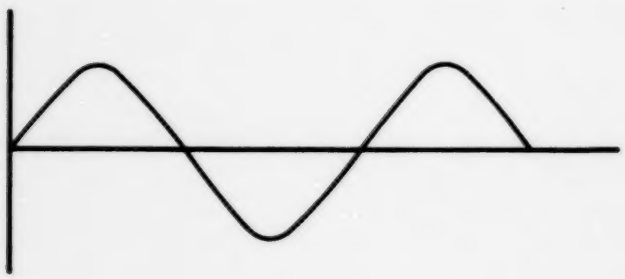


FIGURE 5: Pseudo-Doppler System Block Diagram



(a) FM Demodulated Signal for a Rotating Antenna System

(b) FM Demodulated Signal for a Sampled Antenna System
FIGURE 6

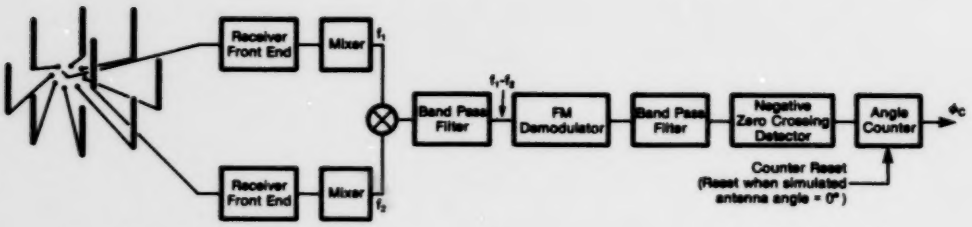


FIGURE 7: Differential Pseudo-Doppler System Block Diagram

2.2.3 Phase Interferometer

The phase interferometer, like the pseudo-Doppler system, uses signal phase difference information from spatially separated antennas to determine the signal bearing. However, unlike the pseudo-Doppler system which processes information from each antenna in succession, the phase interferometer processes information from two or more antennas simultaneously.

The sensor system of the phase interferometer consists of a non-colinear arrangement of at least three dipole antennas. Figure 8 shows the hardware arrangement for each baseline (where a baseline is defined by two antennas). Since a number of different types of standard phase detectors exist, their operation is not discussed here. The output of the phase detector is given by the equation (refer also to Figure 8)

$$\Theta ij = (2\pi dij/\lambda) \cos(\phi - \phi ij) \qquad (17)$$

If no additional information is known, other than Θij, dij, and ϕij, then for a single baseline, ϕ has two or more solutions. By constraining the baseline to a length of one half a wavelength or less, exactly two solutions exist (the correct solution and the correct solution plus 180 degrees).

The correct solution can be resolved by using multiple baselines, with the restriction that not all baselines are colinear (i.e. not all values of ϕij are the same). The following analysis shows how this can be done. Equation 17 can be rewritten in the form

$$\Theta ij = Aij \, Sin(\phi) + Bij \, Cos(\phi) \tag{18}$$

where:

$$Aij = (2\pi \, dij/\lambda) \, Sin(\phi ij) \tag{19}$$

and

$$Bij = (2\pi \, dij/\lambda) \, Cos(\phi ij) \tag{20}$$

N baselines result in a set of N equations of this form. If the terms $Sin(\phi)$ and $Cos(\phi)$ are treated as independent variables, say X and Y, these terms can be determined using standard techniques for solving linear equations (e.g. linear least squares estimate). The computed bearing angle is then given by

$$\phi c = arcTan(Y/X) \tag{21}$$

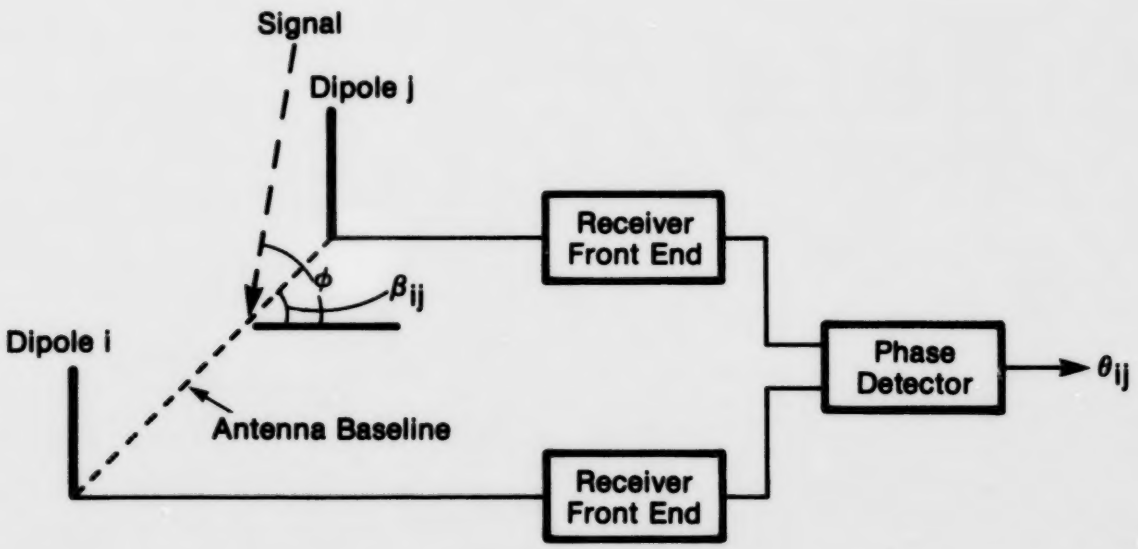


FIGURE 8: Phase Interferometer Baseline Arrangement

Under the ideal conditions considered in this section, only two baselines are required to compute ϕ. However, under realistic conditions where a number of error mechanisms are at work (noise for example), a greater number of baselines results in a better estimate of the true bearing angle.

A basic requirement of multiple baseline systems is that each unique signal direction of arrival results in a unique set of phase measurements to ensure unambiguous bearing measurements. This is a function of the geometry of the sensor system and the spacing between sensors, as well as factors which cause uncertainties in the phase measurements (i.e. noise, measurement errors, etc.). For example, for the geometry shown in Figure 9, neighbouring sensors must be somewhat less than one half wavelength apart or bearing ambiguities may result. A more complete discussion on this subject is given in reference [29].

The most common antenna configuration used in phase interferometer CDF systems is shown in Figure 9. If all six possible baselines are used, it results in six pairs of equations in the form of Equations (19) and (20). Using the linear least squares method to estimate the values of $\mathrm{Sin}(\phi)$ and $\mathrm{Cos}(\phi)$ from these equations, and then computing the estimated bearing angle gives

$$\phi c = \mathrm{arcTan}\left[\frac{\sqrt{2}\phi 13 + \phi 14 + \phi 23 + \sqrt{2}\phi 24}{-\phi 12 - \sqrt{2}\phi 13 + \sqrt{2}\phi 24 + \phi 34}\right] \qquad (22)$$

2.3 Variant Signal Processors

A number of CDF systems have been designed differently than described previously due to engineering considerations such as cost, available technology, system size, etc. Although the principles behind these systems are still the same, the hardware implementations are different.

Three such systems will be discussed: the single channel Watson-Watt system, the dual channel phase interferometer system, and two different single channel phase interferometer systems.

The major difference between the single channel systems and the systems previously discussed is the combining of the sensor outputs into one composite signal so that only a single receiver is required for signal processing. Although this leads to more complicated hardware, the single channel systems have in the past been easier to implement. This stems from the fact that it is difficult and expensive to build two or more tracking receivers that have precisely matched gain and phase characteristics over their full ranges and frequency ranges. Mismatches in gain and phase between signals can cause serious errors in the bearing calculations. Since in single channel systems the input signals share the same receiver channel, the problems encountered in maintaining the correct gain and phase relationships between signals are far less severe.

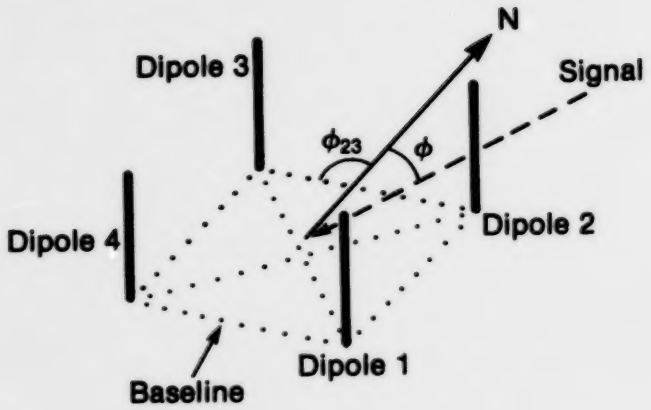


FIGURE 9: Four Element Antenna System Geometry

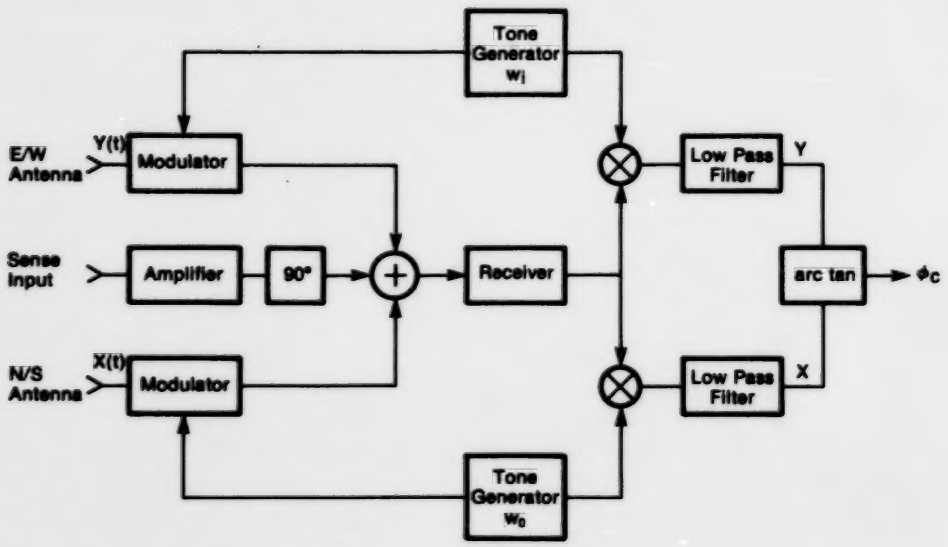


FIGURE 10: Single Channel Watson-Watt System Block Diagram

2.3.1 Single Channel Watson-Watt Systems

Figure 10 shows a block diagram implementation of a single channel Watson-Watt system [4],[5]. In this system the sensor inputs from the directional antennas are modulated by two low frequency tones to give the outputs

$$S1(t) = Vm \cos(\phi) \cos(\omega t) \sin(\omega o t) \quad \text{Volts} \tag{23}$$

$$S2(t) = Vm \sin(\phi) \cos(\omega t) \sin(\omega 1 t) \quad \text{Volts} \tag{24}$$

where:

- ωo - angular frequency of one low frequency audio tone (radians/second),
- $\omega 1$ - angular frequency of second low frequency audio tone (radians/second), and
- Vm - amplitude of signal after modulation (Volts).

(Note that the cosine approximation for the directional antennas has been used here). Shifting the sense signal by 90 degrees, then amplifying and summing it with the modulator outputs gives

$$S3(t) = \cos(\omega t) [Va + Vm (\cos(\phi) \sin(\omega o t) + \sin(\phi) \sin(\omega 1 t))] \text{ Volts} \tag{25}$$

where Va is the amplitude of the amplified sense signal.

In this system, $Va > Vm$ so that the summed signal can be treated as a carrier amplitude modulated by two low frequency (ωo and $\omega 1$) tones. Additionally, the amplitude of these tones is now related to the signal bearing. A standard AM demodulator is used to detect the envelope which gives

$$S4(t) = Ve (\cos(\phi) \sin(\omega o t) + \sin(\phi) \sin(\omega 1 t)) \text{ Volts} \tag{26}$$

where Ve is some arbitrary gain expressed in Volts.

Two synchronous demodulators are used to demodulate the signal and separate the two bearing dependent components, giving:

$$X = Ve \cos(\phi) \text{ Volts} \tag{27}$$

and

$$Y = Ve \sin(\phi) \text{ Volts} \quad (28)$$

The reference signals used in the demodulator are derived from the original modulating tones with the appropriate phase shifts added to compensate for phase delays in the processed RF signal.

Finally the bearing is calculated from the values X and Y using the expression

$$\phi c = \arctan(Y/X) \quad (29)$$

2.3.2 Dual Channel Phase Interferometer System

The dual channel system is very similar to the multi-channel system described in section 2.2.3 except antenna pairs are sampled in turn, rather than simultaneously. This has the advantage of reducing the number of receivers required from being equal to the number of antennas used down to two. The disadvantage is an increase in processing time required to determine the signal bearing.

2.3.3 Single Channel Phase Interferometer System

Figure 11 shows an implementation of a single channel phase interferometer system [6]. Like the dual channel system, antenna pairs are sampled in turn to determine their phase differences. However, the single channel implementation requires the use of only one receiver. Once the phase angles have been determined, the calculation of the bearing angle proceeds as described in section 2.2.3.

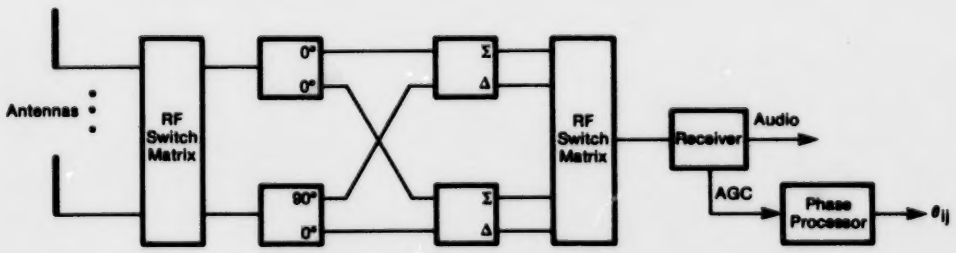


FIGURE 11: Single Channel Phase Interferometer System Block Diagram

To illustrate the operation of this system, assume the outputs from an antenna pair during a measurement period (called the first here) are given by

$$Si(t) = A \sin(\omega o t + \phi/2) \text{ Volts} \quad (30)$$

and

$$Sj(t) = B \sin(\omega o t - \phi/2) \text{ Volts} \quad (31)$$

and during the next measurement period are given by

$$Si(t) = kA \sin(\omega l t + \phi/2) \text{ Volts} \quad (32)$$

and

$$Sj(t) = kB \sin(\omega l t - \phi/2) \text{ Volts} \quad (33)$$

where:

- k - reflects the change in signal level due to amplitude modulation,
- A - voltage gain of antenna i,
- B - voltage gain of antenna j,
- ϕo - angular frequency of signal during first measurement period (radians/second), and
- $\phi 1$ - angular frequency of signal during second measurement period (radians/second).

During the first measurement period, the outputs from the two antennas are summed and fed to the receiver. If the AGC of the receiver has a linear response, the AGC output will be proportional to the amplitude of the sum signal. This can be expressed as

$$Vo = c\sqrt{A^2 + B^2 + 2AB \cos(\phi)} \text{ Volts} \quad (34)$$

where "c" reflects any additional gain to the signal.

During the second measurement period, the difference between the two antenna output signals is fed to the receiver. The resulting AGC signal will be

$$Vi = ck\sqrt{A^2 + B^2 - 2AB \cos(\phi)} \text{ Volts} \quad (35)$$

The two quantities Vo and Vi are then combined in the following manner to give

$$Xij = \frac{Vo^2 - Vi^2}{Vo^2 + Vi^2} \quad (36)$$

Assuming there is no change in signal amplitude between the first and second measurement periods (i.e., k = 1), then

$$Xij = \frac{2AB\ Cos(\phi)}{A^2 + B^2} \tag{37}$$

During the third and fourth measurement periods the sum and difference signals are again used, except this time one antenna output is delayed by 90 degrees. Following the previous analysis, the result is given by

$$Yij = \frac{2AB\ Sin(\phi)}{A^2 + B^2} \tag{38}$$

From these two quantities, Xij and Yij, the phase angle can be calculated using the following expression

$$\phi ij = arcTan(Yij/Xij) \tag{39}$$

By applying this measurement sequence to each baseline, the relative phase angles between each antenna pair can be determined. From this point, the calculation of the signal bearing angle is the same as described in section 2.2.3.

2.3.4 Single Channel Phase Interferometer with Delay Lines

Figure 12 shows an implementation of a single channel phase interferometer that uses delay lines [7]. This system is nearly identical in operation to the single channel phase interferometer just discussed. The major difference is the use of delay lines.

The delay lines have two purposes. Instead of delaying one antenna output alternately 0 degrees and 90 degrees, the delay lines are used to phase shift one antenna output alternately +45 degrees and -45 degrees relative to the other antenna output. The calculation of the measured phase angle between pairs of antennas is exactly the same as described in section 2.3.2.

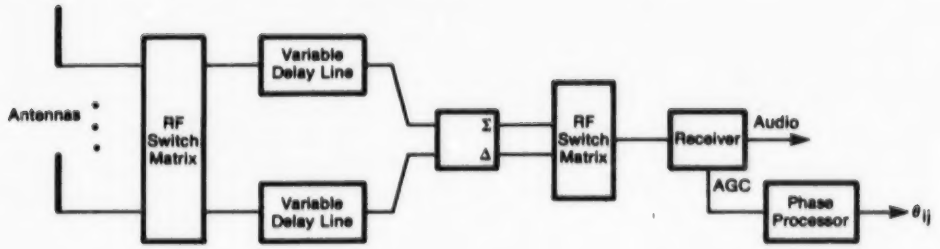


FIGURE 12: Block Diagram of Single Channel Phase Interferometer With Delay Lines

The second purpose of the delay line is to adjust the two antenna output signals to have a 0 degree phase difference before the +45 or -45 degree phase shift is applied. The amount of phase delay required is determined by adjusting the phase delay until the measured phase difference, θm, is 0 degrees. For example, during the first set of measurements, the delay line phase shift setting is 0 degrees. Using the measured value θm, the delay line is adjusted to this value for the second set of measurements. If after the second set of measurements the new value of θm is not 0 degrees, the delay line is adjusted appropriately and another set of measurements is taken. This process is repeated enough times to ensure the delay reaches a steady state value. In most cases, this occurs after only one iteration [8].

Once the delay line has settled, the delay line phase setting is taken to be the correct phase difference. Repeating this for all baselines, the signal bearing angle can then be computed as described in section 2.2.3.

The use of delay lines to create a feedback loop makes this variation of the single channel phase interferometer a closed loop system. The advantage, compared to the open loop system described previously (section 2.3.2), is that the measurement of the phase angle, θm, need only be accurate for phase differences of 0 degrees. This places less stringent accuracy requirements on the equipment, except for the delay line which must be accurate.

2.4 Output Display

The standard method of displaying the bearing is using a digital display with one degree, or one tenth of a degree resolution. Since under actual field conditions the accuracies of CDF systems are typically on the order of several degrees, one tenth of a degree resolution is virtually meaningless.

Another method of display developed for the Watson-Watt system employs a video display driven by the outputs of each of the three channels before demodulation (i.e. after conversion to IF). The sense channel is used to resolve bearing ambiguity, and the other two channels are used to drive the X and Y deflection plates of the video display. The appearance of the display for various conditions is shown in Figure 13. The main advantages of this display are that with some operator skill, it is possible to determine the quality of the signal (i.e. noise, co-channel interference, or multipath) as well as determine the bearings of more than one signal simultaneously.

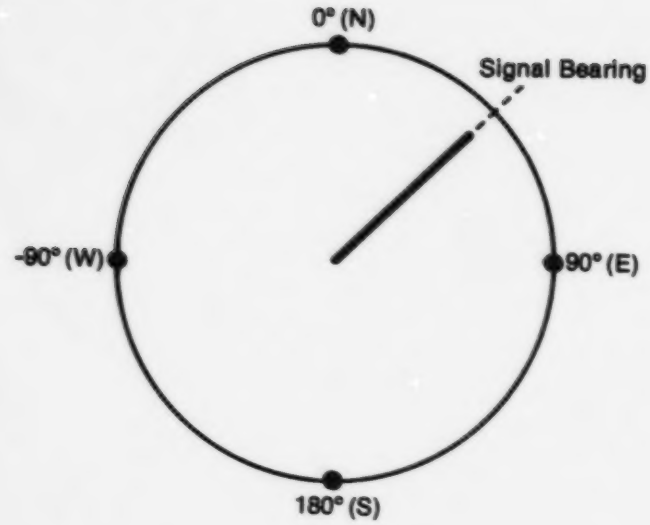
In some systems, a quality factor is also displayed which is based on parameters derived during the direction finding process. For example, the Communication Emitter Location System used by the Canadian Army is a single channel phase interferometer that uses delay lines. In this particular case, the calculation of the quality factor is based upon signal strength, the fit of the delay line settings to the calibration table data (see section 3.7.4 for a discussion on calibration techniques), and the amount of data available for computing the mean bearing [7],[8].

In theory, the quality factor should provide an indication of the amount of potential error in the computed bearing angles. In practice, the quality factor does not always provide a true indication of the potential error. The problem appears to be that the nature of environmental error sources, such as multipath, are not sufficiently understood to be able to make an accurate assessment of the potential bearing errors.

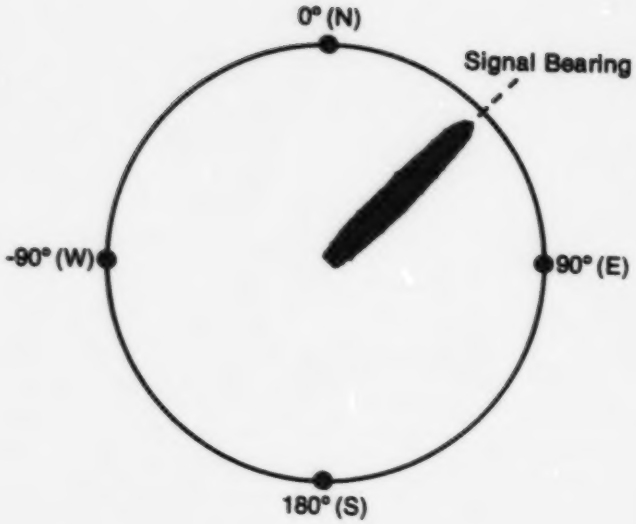
3.0 REAL WORLD PROBLEMS AND SOLUTIONS

The following discussion deals with the problems and solutions encountered in the design and operation of real world CDF systems. The discussion provides an overview of the problems that occur when the assumptions given previously in Section 2.0 breakdown, the source of these problems, and the solutions (if any).

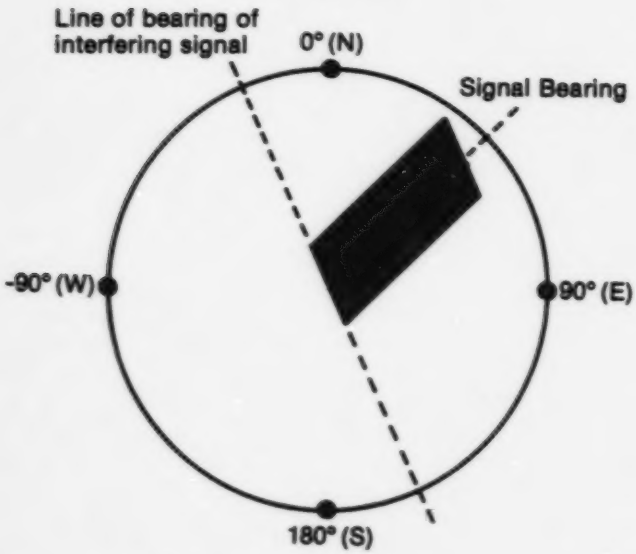
Where more detailed mathematical analysis or the results from computer simulations are provided, they are based on three specific systems. The model used for the Watson-Watt system is based on the system shown in Figure 4a, with the sense signal derived from the sum of the four dipole outputs (Figure 4c). The pseudo-Doppler system model is based on the single channel version shown in Figure 5. The phase interferometer system model is based on Equation (22) (see also Figure 8). Frequency and phase demodulators are based on zero-crossing techniques.



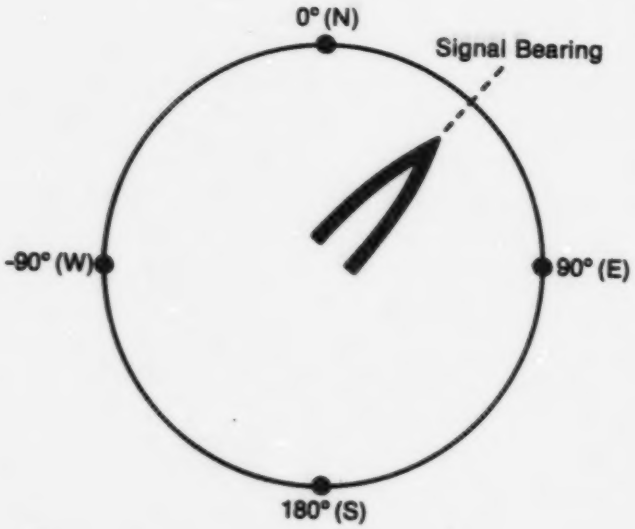
(a) Good Signal



(b) Signal Plus Noise



(c) Signal Plus One interfering signal



(d) Phase mismatch due to channel misphasing, stray pickup, or multipath.

FIGURE 13

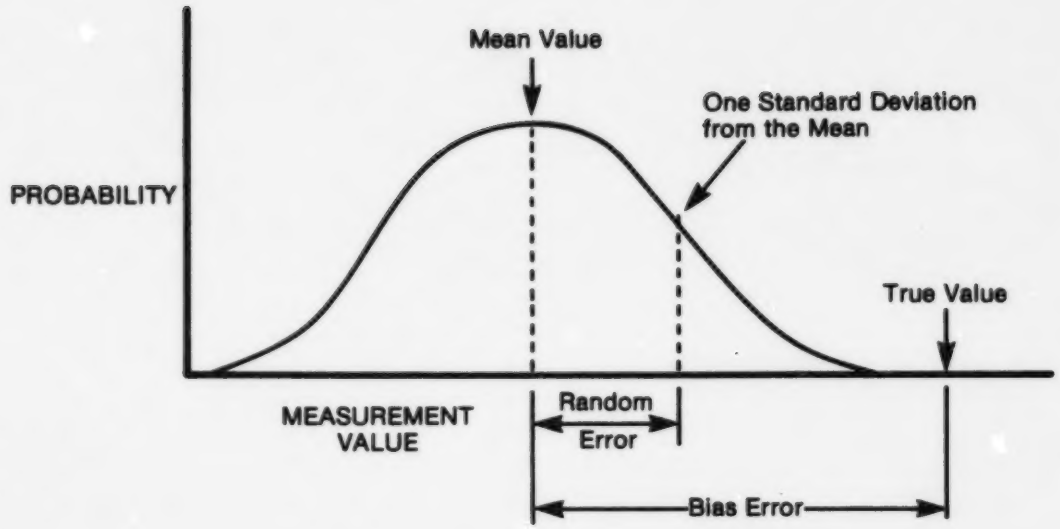


FIGURE 14: Probability Density Function

The antenna systems considered are quad dipole antenna arrays (that is, systems using antenna arrays with 4 vertical dipoles arranged in a square). This is the most popular configuration currently being used and provides a simple way of comparing the results from the different types of CDF systems. Additionally, for the sake of consistency, the diagonals of the antenna array were assumed to be oriented North-South and East-West respectively.

In some cases, the results have been extended to variations of the systems discussed.

3.1 Definition of Terms

Figure 14 shows an idealized probability density function derived by taking an infinite number of bearing measurements of a radio signal. The key features of the distribution are the clustering of the measurements around the mean value and the offset of the mean value from the true value.

Using Figure 14 as a reference, the definition of some of the terms used in this report are as follows:

(a) Mean Bearing - the average bearing derived from the probability density function,

(b) True Bearing - the actual bearing from the CDF system to the transmitter, referenced to true North,

(c) Random Error - the standard deviation of random fluctuations in the bearing measurements due to effects such as noise,
(d) Bias Error - mean bearing minus the true bearing,
(e) RMS Error - root mean squared value based on the difference between the measured value and a reference value (usually the true bearing), and
(f) Accuracy - Standard deviation of the bias errors for a number of measurements.

Since most CDF antenna arrays are circular, the diameter "D" has been used to specify their size.

3.2 Multipath

Multipath occurs when the signal of interest arrives at the receiving antenna via two or more paths. It is also called coherent interference since there is a direct signal (the signal of interest) plus indirect interfering signals, where the interfering signals are delayed copies of the direct signal.

Multipath can occur if any part of the transmitted signal not headed directly towards the CDF system is reflected, diffracted, reradiated, or scattered by physical objects (such as rocks, building, or trees) back towards the CDF system. The characteristics of multipath (i.e. amplitude, phase, bearing, and number of indirect signals) under tactical operational conditions are unknown. However, experimental evidence has shown multipath to be the cause of bias errors in CDF systems on the order of several degrees or more [11].

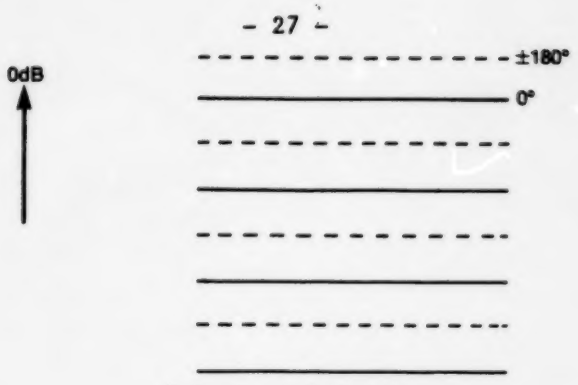
An understanding of the multipath problem can be gained from Figure 15. The illustrations show lines of constant phase relative to some fixed reference point. Unless the various signal paths are changed (normally they are stationary, i.e., rocks, buildings, trees, etc. do not move), the lines are stationary with time.

Figure 15a shows a case where the signal bearing is zero degrees and there are no multipath components. The measured bearing is the normal to these phase lines and agrees with the true bearing (assuming no other error mechanisms).

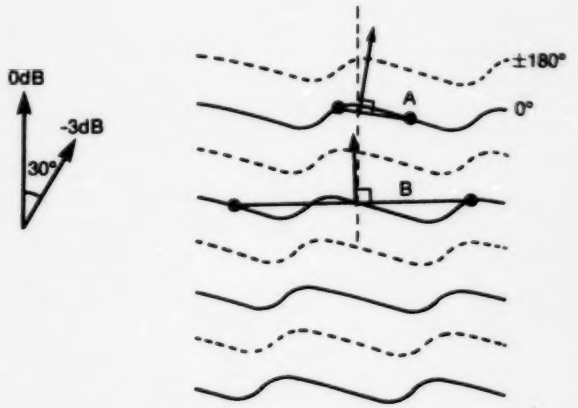
Figure 15b shows a simple case of multipath - the direct signal at a bearing of 0 degrees plus an indirect signal at a bearing of 30 degrees. Since the normal to the phase lines varies with position, the measured bearing will also vary with position. Additionally, since the phase lines do not normally change with time, the resultant bearing errors are position dependent bias errors.

3.2.1 Antenna System Diameter

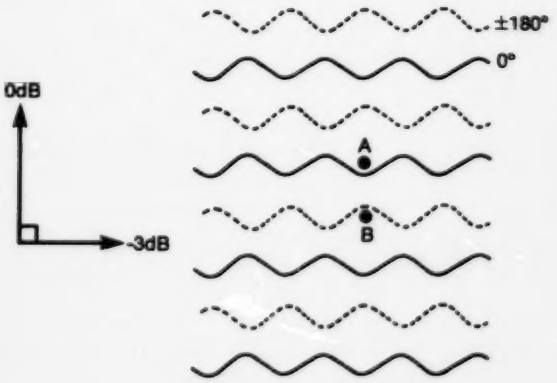
In the case of Watson-Watt systems, changing the diameter of the antenna system has no effect on the bearing errors. However, for the other systems, it does.



(a) No Multipath



(b) Multipath



(c) Multipath.

FIGURE 15: Phase Field Diagram

If the amplitude of the direct signal is greater than the sum of the amplitudes of the indirect signals, averaging the measurements with respect to position can reduce the bias errors. This can be accomplished by increasing the diameter of the sensor system. Comparing the difference in bearing errors for baselines A and B in Figure 15b illustrates this effect.

Predicting the exact effect of increasing the antenna diameter is not possible since a good model of the tactical multipath environment does not exist. However, from theoretical considerations, it is possible to make some generalizations. Increasing the antenna diameter will increase the amount of averaging, which in turn, will result in more accurate bearings. This is also supported by experimental evidence [9]. Additionally, for antenna diameters of less than one half a wavelength of the intercepted signal, spatial averaging is of little benefit. This is discussed in more detail below.

Examining Figure 15a, the spatial frequency (measured in cycles per meter or cpm) along any baseline will depend on the orientation of the baseline with respect to the phase lines. The maximum spatial frequency ($1/\lambda$ cpm) occurs when the baseline is normal to the phase lines and the minimum (0 cpm) when the baseline is parallel to the phase lines. In a complex wave field composed of coherent signals with various bearings, the spatial frequencies of the signals along any one baseline will vary between these two extremes.

Since averaging is equivalent to a low pass filter operation, the effect of spatial averaging is to suppress the multipath components as a function of their spatial frequency. Figure 16 illustrates this suppression. Additionally since the direct signal is not an error signal, the baseline that determines the accuracy of the CDF system is the one closest to being perpendicular to the transmitter bearing (i.e. parallel with the phase lines). In this orientation, the spatial frequency of the direct signal will be almost 0 cpm and not affected by averaging.

In figure 16, the spatial bandwidth of the averager, Fb, is a function of the length of the baseline (or antenna diameter) and is given by the following expression

$$Fb = 1/2D \text{ cpm} \tag{40}$$

Averaging has very little effect if the spatial frequencies of the multipath signal components are less than Fb. Since the power and spatial frequency of each multipath signal components (which depend on their bearing relative to the baseline) is highly dependent on transmitter and CDF system site locations, the advantages of spatial averaging cannot be predicted. However, since the upper frequency limit is defined as $1/\lambda$, the spatial bandwidth must be lower than this value in order for averaging to have any effect. This translates into an antenna diameter of one half a wavelength or more.

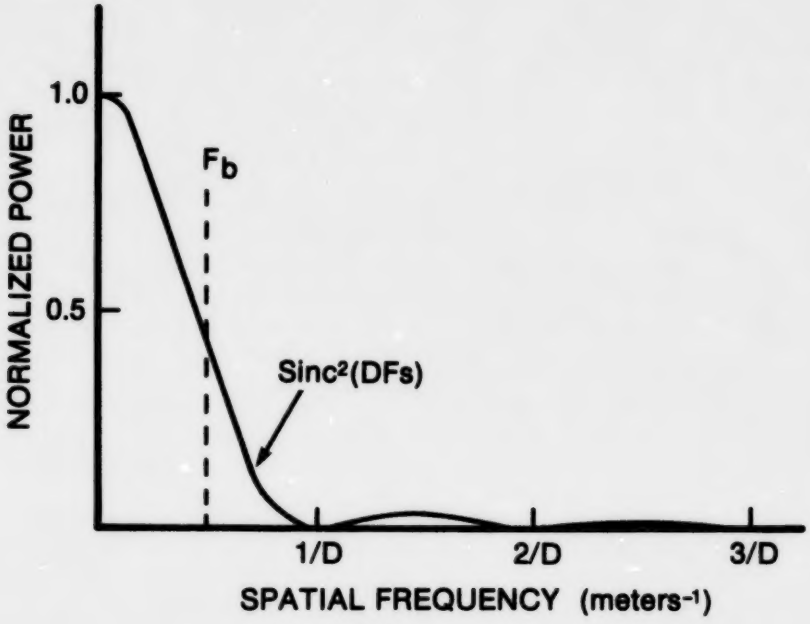


FIGURE 16: Power as a Function of Spatial Frequency

The result is that since most CDF systems have diameters smaller than one half a wavelength, the improvement due to spatial averaging is insignificant (i.e. less than a 50% reduction in RMS bearing errors in comparison to a system with an infinitely small diameter). However, there are a few tactical antenna arrays with diameters greater than this. An example is the PA 007 pseudo-Doppler antenna array built by the Rohde and Schwarz Company [10]. This is a 32 element array designed to operate in the 100 to 162 MHz range. With a diameter of 6 meters, the diameter of the array is 3.2 wavelengths at 162 MHz, and 2.0 wavelengths at 100 MHz.

3.2.2 Elevated Sensor Platforms

Experimental work has shown that a significant amount of multipath can be close to the CDF system [11], [12]. One way to reduce this effect is by raising the sensor platform above the earth. By increasing the distance between the sensor system and nearby re-radiators, the re-radiated energy received by the CDF system can be reduced. In comparison, the change in the distance to the transmitter will not be significantly effected. In fact, since raising the sensor system can result in a less obstructed signal path between the transmitter and the CDF system, an increase in direct signal power may occur. The end result is a greater immunity to bearing measurement errors caused by multipath conditions.

Although higher is better, size and weight requirements restrict antenna masts to heights of up to about 20 meters. Additionally, raising the antenna can also increase the power of signals received from transmitters, other than the target transmitter, operating at the same frequency (i.e. co-channel interference) and this in turn can degrade the accuracy of the bearing measurements.

3.2.3 Phase Measurement Errors

Figure 15c illustrates a measurement problem that can occur under some conditions. In this situation, dipoles A and B have been designed to be spaced less than one half a wavelength apart so that the absolute phase difference between the two dipoles will be less than 180 degrees. However, due to the curvature of the phase lines, the absolute phase difference in this particular case is greater than 180 degrees. Consequently, the measured phase will be incorrect (off by 360 degrees). Unless this error is corrected by some other means, the resultant bearing error may be as much as 180 degrees.

Since this type of phase error occurs more often as the spacing between the dipoles approaches one half of a wavelength, the spacing between adjacent dipoles in CDF arrays are usually restricted to 0.4 wavelengths or less.

3.3 Co-channel Interference

Co-channel interference occurs when one or more interfering signals are at or near the same frequency as the primary signal of interest (i.e. within the receiver passband). It is similar to multipath except that the interfering signals are incoherent; that is, the amplitude, frequency, and/or phase characteristics of the interfering signals have no relationship to the signal of interest (uncorrelated).

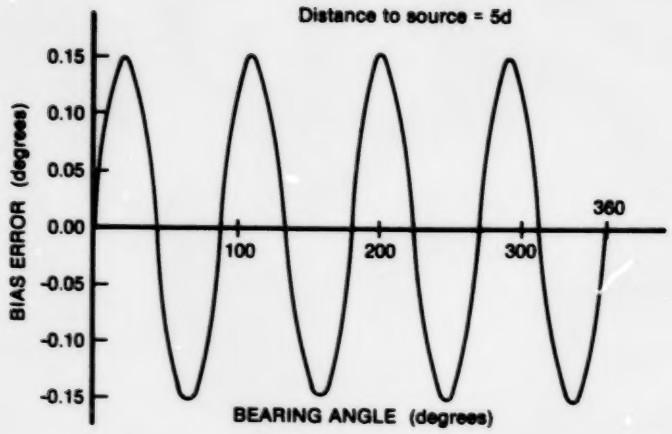
Like multipath, co-channel interference can also be analyzed in terms of phase lines as illustrated in Figure 15. The main difference between this and the multipath case is that since the interfering signals are incoherent, the phase pattern is not stationary with respect to time.

In comparison to the multipath case, the improvement in accuracy versus antenna system diameter is the same. Additionally, the problems with phase measurement errors that occur for dipole spacings near one half of a wavelength are also the same. The major difference is that since the phase lines are not stationary, the bearing errors vary with time; that is, they are random errors.

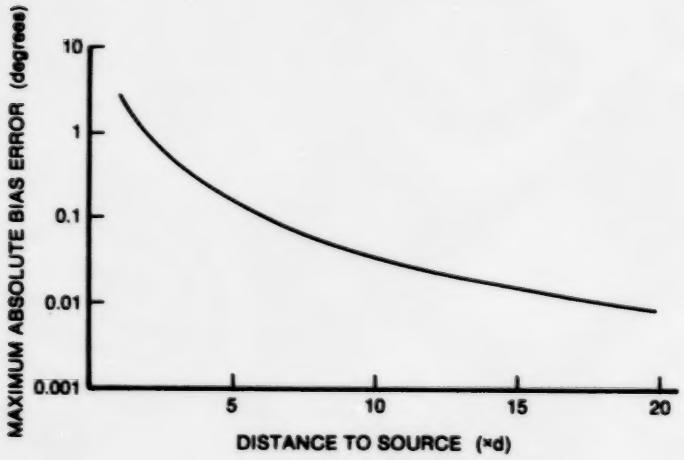
As long as more than half the received signal power is in the signal of interest (otherwise the system may lock onto the wrong signal), and phase errors do not occur, the bearing fluctuations can be treated as noise and filtered out. The statistics of this noise will depend on the frequency, modulation, and power of the signals involved. A detailed analysis is beyond this report, however, a discussion of various types of noise and the effects of noise filtering are given in Section 3.8.

3.4 Curvature of the Signal Wavefront Due to Range

In the discussion on theory of operation of CDF systems it was assumed that the signal wavefront could be modelled as a planar waveform. This approximation becomes erroneous if the CDF system - the sensor system in particular - is located too close to the signal source compared to the diameter of the antenna array.



(a) Bias Error as a Function of Antenna Orientation



(b) Bias Error as a Function of Distance

FIGURE 17: Wavefront Curvature Errors Due to Short Distances Between Receiver and Transmitter

The effect on the bearing measurements is to cause bias errors that are dependent on both the direction of the signal and the distance to the signal source. Using the computer models, the magnitude of these errors are illustrated in Figure 17. These results are independent of signal frequency.

Due to the symmetry of the antenna geometry with respect to the signal wavefront, measurement bias errors cancel out at bearing intervals of 45 degrees, starting at 0 degrees. For systems using greater numbers of dipole elements in a circular configuration (e.g. 8 element pseudo-Doppler arrays), the number of 0 degree error points is greater and the maximum error smaller.

For tactical systems, wavefront curvature errors due to range are not a consideration. Under wartime conditions, if an enemy transmitter was close enough to cause errors greater than 0.1 degrees, he is close enough to see!

3.5 High Elevation and Polarization Errors

Ideally CDF sensor systems are insensitive to horizontally polarized signals and high elevation angle signals. This is a desirable feature since generally, for landbased tactical systems, the direct signal is vertically polarized and arrives at a low elevation angle. High elevation components and horizontally polarized components occur only as a result of reflection, diffraction, reradiation, etc. of the signal. Since indirect signal components cause errors, suppression of these components is desirable.

Vertical dipole antennas have a sensitivity that decreases approximately as the cosine of the signal elevation angle. Under normal conditions high elevation angle signals are not a factor in the VHF/UHF range. However, under some unusual conditions (e.g. in northern or southern regions during auroral activity, signals in the 100-450 MHz may be reflected off the ionosphere) it is possible for high elevation angle signals to cause errors identical to those discussed under multipath.

Theoretically, vertical dipole antennas are insensitive to horizontally polarized signals. However, feed lines joining the antennas are susceptible to picking up unwanted horizontally polarized signal energy. This in turn can affect the phase and amplitude of the antenna output signal and ultimately the bearing measurement.

Methods of reducing stray pick up include proper grounding of the equipment, minimizing the distance between the antenna system and receiver(s) or placing the first signal amplifying stage right in the antenna head, correctly matching impedances in the antenna system over the frequency band of operation, and elevating the sensor system (discussed previously).

3.5.1 H-Adcock

Another method of reducing horizontal polarization effects for the Watson-Watt system is illustrated in Figure 18. Here a crossed H configuration is used for the Adcock antenna. In this version, horizontal signals picked up in each of the split dipoles is exactly the same. Since the output of the Adcock antenna is the difference between the two dipole signals, the horizontal components from each dipole cancel out.

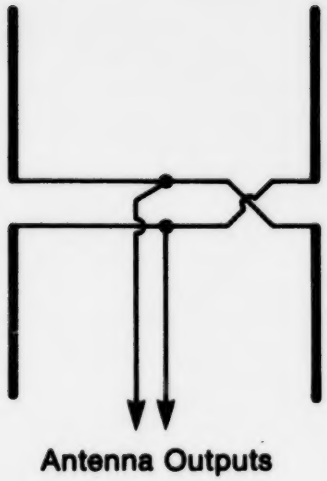


FIGURE 18: H-Adcock Antenna

3.6 Modulated Systems

Up to this point CW signals have been mainly considered. Since the tactical signals of most interest are modulated (e.g. AM, FM, SSB, etc.), the effects of modulation are important consideration. Of the systems discussed, two are modulation sensitive: the single channel pseudo-Doppler system, and the single channel phase interferometer (closed loop and open loop).

For the single channel pseudo-Doppler system, changes in signal frequency, which occur in FM and SSB signals, cause bearing errors. This is because the system samples a circular array of antennas sequentially in order to phase modulate the RF signal. Since the discriminator cannot distinguish between transmitter modulation and modulation due to the CDF process, errors result.

For the single channel phase interferometer systems, changes in signal amplitude, which occur in AM and SSB signals, cause bearing errors. This is because phase measurements depend on the RF signal amplitude remaining constant while the sum and difference signals between a pair of antennas are being measured. If the amplitude does change, errors in the phase measurements, and consequently the bearing calculations, result.

Bearing errors resulting from modulation of the RF carrier can be analyzed in a manner similar to errors resulting from noise. The statistics of this modulation "noise" are dependent on the modulation type, the amount of modulation, and the information content. A more detailed discussion on noise is given in Section 3.8. Noise filtering techniques which are used to suppress these modulation effects are also discussed. An example of the usefulness of this method is the Watkins-Johnson WJ-8975A, a single channel pseudo-Doppler system. In tests at DREO, the noise filter was able to completely suppress the modulation effects of a voice modulated FM signal (the integration time constant was 2 seconds).

In the other CDF systems discussed, signal modulation can actually be beneficial for two reasons. The first reason is that signal modulation results in an averaging of the bearing measurements over a band of frequencies. Since multipath conditions and imperfections in the CDF equipment cause bias errors that vary with frequency, this frequency averaging, in general, results in a better estimate of the true bearing. Unfortunately, for narrowband signals (100 kHz or less) the improvement is generally insignificant.

The second reason (discussed previously in Section 2.4) is that if a video display is used to display the orthogonal bearing components of the signal, it is often possible to determine the direction of non-coherent interfering signals (as well as the signal of interest) from the display.

3.7 Equipment Errors

A number of sources of bearing error are a result of the equipment itself. A description of errors due to the orientation of the sensor system, non-ideal responses of the sensor system and receiver, as well as a method of reducing the impact of these errors, follows.

3.7.1 Orientation Errors

One aspect of CDF systems not previously discussed is the method used to determine the orientation of the sensor system with respect to true north. The most common method is to align the system using the Earth's magnetic field and then apply an offset equal to the local magnetic deviation to the bearing measurements.

Systems that use the Earth's magnetic field to determine antenna orientation employ either a compass or a flux gate magnetometer. The compass is used to manually align the antenna using magnetic north as a reference. Systems using the fluxgate magnetometer are more sophisticated. They continuously monitor the antenna system orientation and apply the appropriate correction to the bearing measurements automatically.

Another method of orienting the sensor system is by sighting on a known distant object. Using a map, the bearing of the distant object can be determined, and the sensor system then correctly aligned.

Errors in orienting the sensor system are critical since they translate directly into bias errors in the bearing measurements. Random errors can also result, in the case of the fluxgate magnetometer, when high winds shake the sensor system.

3.7.2 Sensor Errors

The antenna system is a source of bias errors. Adcock antenna arrays do not precisely follow the ideal cosine directional response. The error introduced into the measurements is a function of the signal wavelength and is shown in Figure 19.

Radiation, diffraction, scattering or reflection of signals by the antenna dipoles and the rest of the CDF system (multipath) can affect the amplitude and phase of the received signals. Elevating the antenna system several wavelengths above the rest of the CDF system (up to 20 meters or more - which is two wavelengths at 30 MHz) can reduce the effect of the CDF equipment. The effect of the antenna dipoles (also called mutual coupling) can be reduced by properly matching the antennas over the entire frequency band of operation of the CDF system. One method of accomplishing this is by resistively loading the antenna dipoles; an example of this is given in reference [13]. However, this results in a loss of antenna gain and lower sensitivity. In Watson-Watt systems using twin 4-element Adcock antennas, the effects of mutual coupling can be reduced through careful selection of antenna half angles [14].

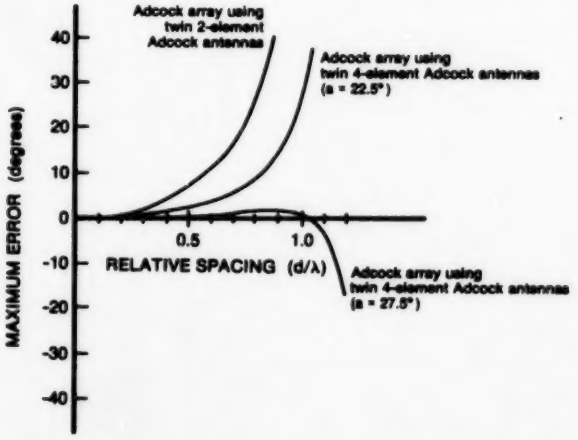


FIGURE 19: Adcock Antenna Errors
(Mutual Coupling Effects Have Been Ignored)

At UHF frequencies the wavelengths are small enough that shadowing of the antenna elements by the antenna mast can occur. This can cause gain imbalances between shadowed and unshadowed elements of the order of 20 dB or more, which in turn can cause errors of several degrees or more in the bearing measurement [15].

Other problems include impedance mismatches between the antenna and the rest of the CDF system, misalignment of the antenna elements, and poor matching of phase and gain characteristics between separate antennas. Careful attention to the design and construction of the antenna system is required to keep the effects of these problems on the bearing measurements to a minimum.

3.7.3 Receiver Errors

Ideally, the gain characteristics of the receiver channels are linear and the delays are constant over the signal bandwidth, so that the receiver output signal is a good representation of the signal of interest. Additionally, in multichannel systems, the gain and phase characteristics of each channel would be matched to preserve the correct relationship between signals in different channels.

In real world systems it is impossible to meet these requirements, and the result is bias errors in the bearing measurements. For example, a 4% error in the measurement of the amplitude of one Adcock antenna output could result in a bearing error of up to 1 degree in a Watson-Watt system. Similarly, in the measurement of phase differences of a four element phase interferometer, a 4% error along a single baseline (which equates to 1 and 5 degree phase errors for antenna system diameters of 0.5 and 0.1 wavelengths respectively) could result in bearing errors up to 1 degree.

If the variations from ideal responses are small enough, the corresponding errors in the bearing measurements will be tolerable.

3.7.4 System Calibration

Since the measurement errors that have been described are bias errors, they can by corrected to some extent by calibrating the system. There are two methods commonly used to calibrate CDF systems.

The first method compensates for time variant system errors. A calibration circuit simulates a signal arriving from a known direction (usually 0 degrees). The operator adjusts a bearing offset control until the diplayed bearing is correct.

The second method compensates for time invariant frequency and bearing dependent errors. This procedure works by comparing the calculated bearing, or the output of an intermediate stage, to the values in a calibration table that has been organized on the basis of bearing versus frequency. By comparing the measured data with the calibrated data at the appropriate frequency, the correct bearing can be determined. This is done by finding the closest match between the measured data and the calibrated data. By interpolating from the calibrated data using the closest match and its neighbours, a good estimate of the bearing position can be made. Once the apparent bearing position of the measured data has been determined, the corrected bearing angle can be found.

To generate the look-up table, the CDF equipment is placed on a large turntable at a calibrated site (i.e. site errors are accounted for). A transmitting antenna transmits a signal at one frequency while the turntable is slowly turned 360 degrees. Bearing measurements are taken at fixed angle increments and the appropriate measurements are stored in the table. The frequency is incremented and the process is repeated until the entire frequency range has been covered. For example, ESL makes calibration measurements every 3 degrees for each of 30 frequencies to cover the 20-150 MHz band of the Canadian Army's Communications Emitter Location System (a single channel phase interferometer system which uses delay lines) [8].

Since there is often some uncertainty in the measured bias errors due to random effects such as noise, the calibration data is smoothed to remove extraneous values, and then stored in memory in a tabular form.

The smaller the direction and frequency increments in the calibration process, the more accurate the method, since interpolation errors will be reduced. However, the increase in accuracy comes at the price of more calibration data, larger memory, and increased processing time.

The methods of calibration described here compensate for a large percentage of the measurement bias errors introduced by the equipment. In fact, calibration can reduce equipment errors from several degrees to less than a degree. However, bias errors introduced into the measurements by changes that occur over time and which are dependent on frequency, bearing, phase, or amplitude, etc., can not be compensated for by the calibration methods discussed.

3.8 Noise

The effect of noise on the performance of CDF systems is to degrade the accuracy and precision of the bearing measurements. The major sources of noise in the VHF/UHF band are shown in Figure 20 [16]. The levels shown in Figure 20 are the noise levels that would be measured at the output terminals of a dipole antenna matched at all frequencies.

Of primary interest to CDF systems are three types of noise: internal noise, extraterrestrial noise, and man-made noise. A description of these types of noise follows.

Internal noise is generated primarily in the input section of the CDF system which includes the first amplifying stage of the receiver. There are three distinct sources of internal noise (for solid state devices), namely, flicker noise, shot noise, and thermal noise [17].

Extraterrestrial noise is produced by a large number of radio sources distributed principally along the galactic plane (galactic noise) plus noise from the sun. The noise contribution from the sun is variable and periodic with an eleven year cycle. It generates the highest noise levels during periods of peak sunspot and solar flare activity.

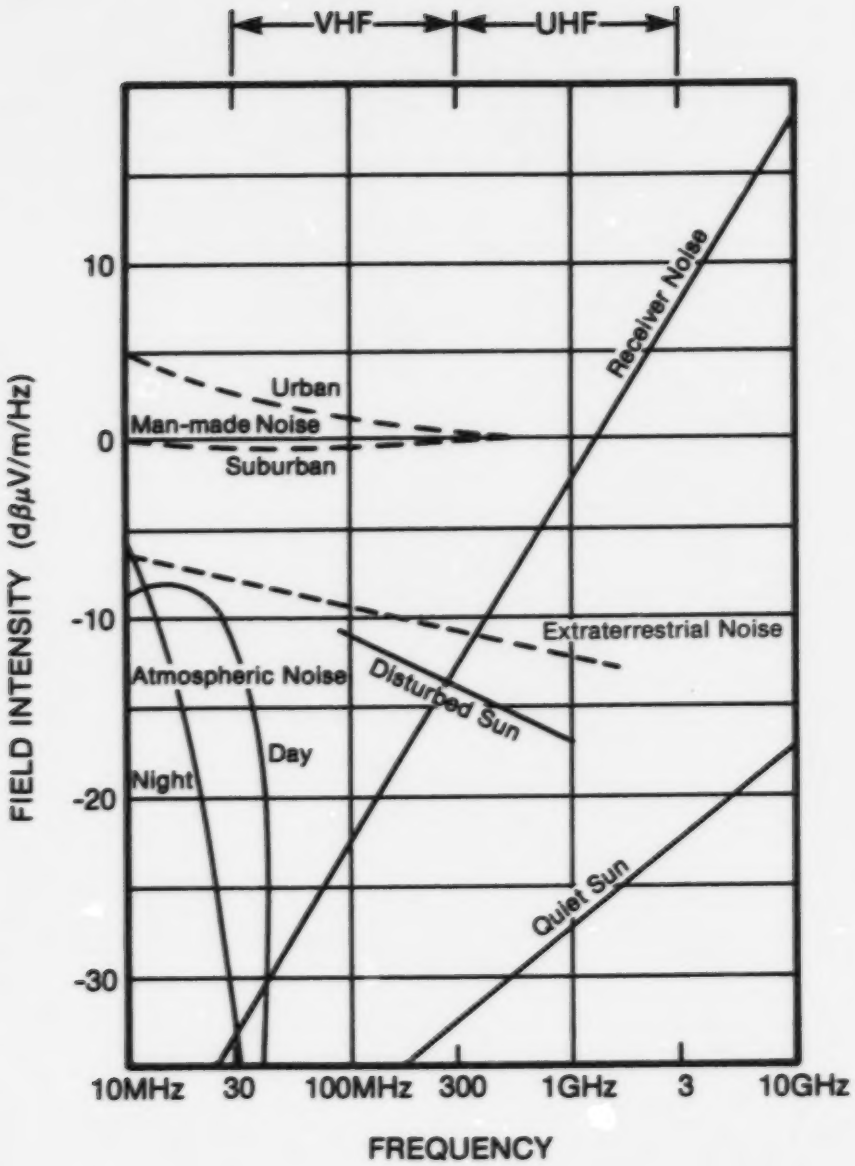


FIGURE 20: Noise Levels

(reprinted, with permission, from "Electromagnetic Interference and Compatibility", Volume 5, by W.G. Duff and R.J. White)

Man-made noise is produced by intentional radiators such as radio stations, radars, radio beacons, etc., as well as unintentional radiators such as power lines, electric tools, fluorescent lights, etc.

The major differences between the three types of noise described are in the statistical nature of the noise. Depending on the type of noise that dominates, this, in turn, affects the statistical nature of the resulting bearing errors.

Internal noise can be accurately modelled in the VHF/UHF band as white Gaussian noise. Ignoring noise components outside the CDF system passband, the internal RMS noise can be described using the equation

$$Pn = 30 + 10\text{Log}(kTB) + F \text{ dBm} \quad (41)$$

where:

k - Boltzman's constant (1.38×10^{-23} joules per K),
T - temperature (293K at room temperature),
B - bandwidth (Hz), and
F - noise figure of receiver (typically about 10 dB).

Extraterrestrial and man-made noise can be modelled in the VHF/UHF band as white Gaussian noise plus impulse noise [18],[19]. Of the two types, man-made noise is generally more impulsive in nature. However, the strength of the impulse component is highly dependent on the exact nature of the noise sources. The approximate RMS noise levels of man-made and extraterrestrial are shown in Figure 20.

The type of noise that dominates, is dependent on frequency, location, and antenna gain. The effects of frequency and location are apparent in Figure 20. Additionally, although not shown, man-made noise levels in remote rural areas are typically lower than extraterrestrial noise levels. Antenna gain affects the ratio between internal noise and external (man-made plus extraterrestrial) noise. In operational CDF systems, design constraints result in antenna systems that do not have optimum gain characteristics over the complete operational frequency spectrum as was assumed in Figure 20. Consequently, in some systems (especially in quiet rural environments) internal noise may be stronger than the external noise.

It should be recognized that Figure 20 does not indicate man-made noise levels for the tactical wartime environment. Wartime levels would doubtlessly be greater, but the actual levels are impossible to predict.

3.8.1 Effect of Internal Noise on Bearing Measurements

To examine the effects of internal noise alone, the theoretical performance of each of the three CDF systems in the presence of internal noise was simulated on a computer. Noise was considered to be the only error producing mechanism.

Figure 21 shows the results. The signal to noise ratio refers to the levels measured at the output of each dipole element (which were equal for all four dipoles). These values can be converted to the corresponding maximum signal to noise ratios at the output of an Adcock antenna using the expression

$$SNR(Adcock) = SNR(Dipole) + 20Log(Gain/\sqrt{N}) \text{ dB} \quad (42)$$

where for a twin 2-element Adcock antenna system the parameter "Gain" is given by equation (3) and N = 2, and for a twin 4-element Adcock antenna system the parameter "Gain" is given by equation (5) and N = 4. The errors shown are for a single measurement without noise filtering (as discussed in Section 3.8.3).

In Figure 21 the noise was additive white Gaussian noise generated internally (i.e. the noise voltages measured at each dipole were uncorrelated). In this case the response of the three different systems was almost identical.

For signal to noise ratios greater than 10 dB, and antenna array diameters one half wavelength or less, the RMS bearing errors due to noise can be approximated by the formula

$$\text{Error} = 10^{-SNR/20} * 90\lambda/(\pi^2 D) \text{ degrees} \quad (43)$$

where SNR is the signal to noise ratio in dB.

At signal levels less than 10 dB, multiplication of the noise with itself (called multiplicative noise) in nonlinear operations (such as receiver detector circuits or the arc tangent operation) begins to dominate. The result is a decrease in the signal to noise ratio and a change in the frequency distribution and bandwidth of the noise. Modelling these effects is beyond the scope of this report since it is specific to the exact manner in which the bearing is actually generated. The result, however, is poorer accuracy than would be expected otherwise.

At very low signal levels, the bearing error levels off as it approaches the upper limit (104 degrees is the RMS error when the bearings are completely random, that is, equally distributed in all directions).

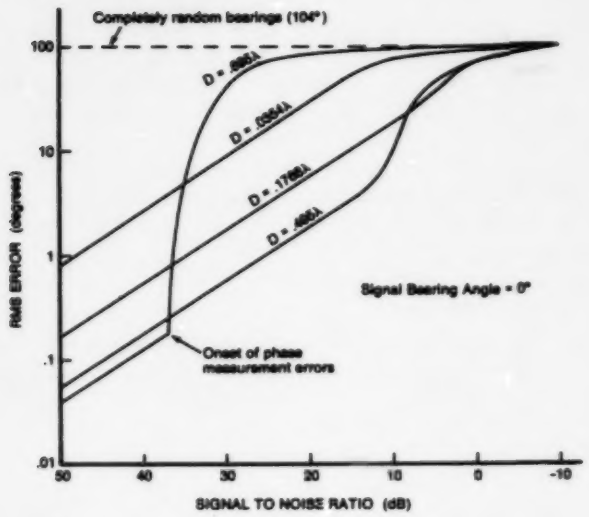


FIGURE 21: Bearing Measurement Errors in the Presence of Noise

When the spacing between adjacent dipoles approaches the half wavelength limit (or the diameter for a quad dipole system approaches 0.707 wavelengths), random bearing errors on the order of 180 degrees occur which are a result of phase measurement errors (i.e. the addition of noise to the signal causes the phase difference between adjacent dipoles to exceed 180 degrees). For example, in Figure 21 for systems using antenna diameters of 0.695 wavelengths, the RMS bearing error increases rapidly at signal to noise ratios less than about 38 dB. Since the phase is incorrectly measured this way less than 50% of the time, and the resultant bearing errors are large, it suggests that at signal to noise ratios greater than 10 dB, a series of measurements could be sorted to choose the correct measurements and give the results predicted by Equation (43).

3.8.2 Effect of External Noise on Bearing Measurements

External noise can be regarded as being a type of co-channel interference, i.e. a number of independent sources generating interfering signals in the band of interest. To the CDF system these signals are essentially RF signals modulated by noise with a bandwidth equal to the CDF receiver bandwidth (this is the narrowband approximation for a noise signal [20]).

The main difference between internal noise and external noise, other than signal statistics (i.e. Gaussian versus impulsive), is the correlation between antenna dipole voltages. Internal noise is assumed to be uncorrelated regardless of antenna spacings. External noise is totally correlated for antenna spacings of 0 wavelengths, and gradually becomes uncorrelated as the spacing is increased. The distance at which the noise becomes totally uncorrelated is dependent on the distribution of noise source bearings in azimuth and the relative amplitudes of the individual noise components with respect to each other.

A comparison of the RMS bearing errors caused by uncorrelated Gaussian noise and uncorrelated impulsive noise using computer simulations, found the differences to be negligible.

In the case of the Watson-Watt system, the RMS errors resulting from external noise do not change with diameter. In computer simulations where the noise sources were uniformly distributed in azimuth, the RMS errors caused by external noise were equivalent to those of internal noise for array diameters of about 0.4 wavelengths.

In the case of the single channel pseudo-Doppler system, measurements are made sequentially, so that the noise measured at each dipole will be uncorrelated regardless of the antenna spacing. Consequently, in this case, external noise has the same effect as internal noise.

For the other systems, an analysis of antenna system diameter versus reduction in RMS error is the same as for the case of co-channel interference. The most notably fact is that for diameters less than half a wavelength, spatial averaging has little effect. Additionally, phase measurement errors are also identical to the co-channel interference case.

In systems having diameters greater than one half a wavelength, and where noise source bearings are uniformly and diffusely distributed in azimuth (such as for extraterrestrial noise), the reduction in RMS bearing errors is proportional to the inverse of the antenna system diameter. Additionally, for these diameters and noise bearing distributions, the noise is also uncorrelated [21].

In general, for small diameters (less than one half a wavelength) the RMS bearing errors caused by external noise will be less than those caused by internal noise for the same signal to noise ratios. At distances where the antenna noise generated voltages become uncorrelated, the effect of external noise is the same as internal noise.

3.8.3 Noise Filtering

Figure 21 predicts poor accuracies for CDF systems (4 degrees or more) even at signal to noise ratios as high as 20 dB. (All signal to noise ratios in this discussion are measured at the dipole outputs.) The accuracy of these systems, however, can be improved by filtering out the noise components. In this discussion, this improvement is expressed in terms of an equivalent increase in the input signal to noise ratio which is called the processing gain.

Viewed in the frequency domain, the inputs to the CDF system consist of a signal plus white noise. For signal to noise ratios of 10 dB or more, the bandwidth, frequency characteristics, and relative power of the noise do not change significantly throughout processing (i.e. remains white). Hence, the processing gain can be expressed as

$$PG = 10 \text{ Log}(B\omega i/B\omega o) \text{ dB}, \tag{44}$$

where $B\omega i$ is the input noise bandwidth (in Hertz) of the CDF system (e.g. receiver bandwidth) and $B\omega o$ the noise bandwidth (in Hertz) of the noise filter. Additionally, the signal of interest is assumed to fall completely within the bandwidth of the filter. Typical processing gains range from 20 to 50 dB.

In most systems, the noise filter is used after the processed signals have been converted to baseband. In these cases a low pass filter is used which is the time domain equivalent of an integrator. The bandwidth of the filter is given by

$$B\omega o = 0.25/\tau \text{ Hz} \tag{45}$$

where τ is the integration time constant in seconds. The maximum achievable processing gain can then be expressed as

$$PG = 10 \text{ Log}(4\tau Br) \text{ dB} \tag{46}$$

where Br is the receiver bandwidth in Hertz.

In many cases the input bandwidth to the noise filter is smaller than the receiver bandwidth due to the nature of the measurement equipment. This results in a lower processing gain. For example, in the single channel phase interferometer system, the inputs are not monitored continuously, but only a percentage of the time. The input bandwidth at the filter can then be expressed as

$$B\omega i = aBr \text{ Hz} \tag{47}$$

where a is the percentage of time any one sensor is monitored.

Other examples of lower input bandwidth are found in the pseudo-Doppler system. In the single channel system only one complete set of phase measurements can be made each commutation cycle. The noise filter is placed after the FM discriminator, (if it were placed before the FM discriminator the filter would remove useful signal energy as well as noise) so the value that should be used for the input bandwidth is given by

$$B\omega i = Fc/2 \text{ Hz} \tag{48}$$

where Fc is the commutation frequency in Hertz.

In the differential pseudo-Doppler system, the noise filter is placed before the FM discriminator. It is a bandpass filter centered at the commutation frequency. Since the effects of transmitter modulation have already been removed at this point only the noise is suppressed by the filter. The input bandwidth to the filter will be given by

$$B\omega i = Br/N \text{ Hz} \quad (49)$$

where N is the number of dipoles sampled in the antenna array.

The above equations for bandwidth plus Equation (45) can be used to predict the performance of CDF systems where the input signal to noise ratios at each dipole output are greater than 10 dB. Figure 22 shows an example of the actual noise sensitivity of the Watkins-Johnson WJ-8975A single channel pseudo-Doppler system, compared to theoretically calculated values.

Below signal to noise ratios of 10 dB, the performance of CDF systems and the effect of noise filtering is dependent on the exact implementation of the system. However, from Figure 22 it is apparent that a noise filter is still a very effective noise reduction element in the system.

4.0 SPECIFICATIONS

Ideally, the manufacturer supplied specifications give some indication of the performance that can be expected from a particular CDF system, and a means by which to compare competing systems. Table 1 gives a sampling of the specifications (pertinent to the discussion in this report) of a number of different types of commercial CDF systems. A discussion of the meaning of each one of these specifications and their significance is given in the following sections.

4.1 Sensitivity

The sensitivity of a CDF system is typically expressed in one of two ways: the minimum signal to noise ratio required at the receiver inputs for a given error, or the minimum field strength at the antenna required for a given error. In either case, the limiting factor is assumed to be the internal noise of the CDF system - external noise is ignored.

The stated bearing error reflects the RMS difference between the bearing angle measured at a high signal level (e.g. -60 dBm measured at the receiver inputs) compared to the bearing error measured at the stated sensitivity. The error is usually expressed as a limit (e.g. $\pm$2 degrees) or as a RMS value. Unless otherwise indicated, these two values are equivalent.

The theoretical sensitivity of CDF systems using quad dipole arrays is shown in Figure 21, and is a function of the signal to internal noise ratio, which was discussed previously. In real systems, nonlinear effects in the receiver at low signal levels cause bias errors in the bearing which also contribute to the RMS error.

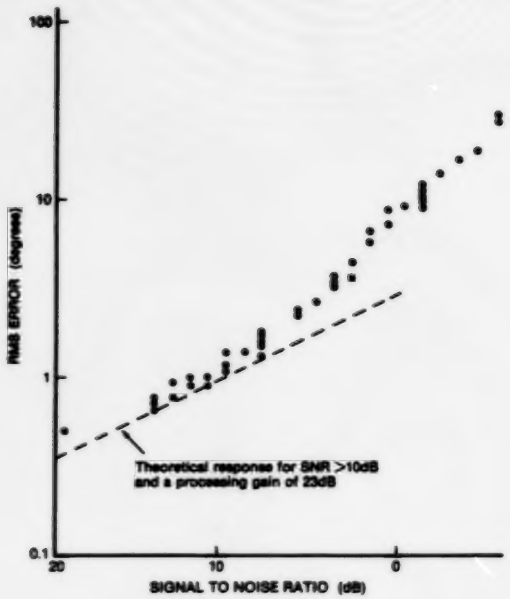


FIGURE 22: Noise Response of the WJ-8975A Pseudo-Doppler direction finding system

In theory, the signal to noise sensitivity measurement provides a method of comparing CDF systems independent of their antenna systems (although the receiver is assumed to be connected to a matched antenna). The sensitivity measurment expressed in terms of the external field strength, on the other hand, allows direct comparison between complete CDF systems (including their antenna systems). The relationship between the two measurements is given by

$$S = 20\text{Log}(LE) - Pn - 107 \text{ dB} \quad (48)$$

where:

S - sensitivity in terms of the signal to noise ratio (dB),
E - sensitivity in terms of the field strength (μV/m),
L - antenna transfer function (m) = (antenna output voltage into 50 ohms)/E, and
Pn - noise power (dBm).

Unfortunately, the conversion requires knowledge of the receiver bandwidth and noise figure (see Equation (41)) as well as the transfer function of the antenna. Since typically not all these values are stated, it is difficult to compare the two types of sensitivity measurements.

Lack of knowledge of the receiver bandwidth during testing also precludes comparison of any of the sensitivity measurements with the equivalent measurement made for other systems. In the case of the signal to noise measurements, increasing the bandwidth increases the processing gain,

which ultimately improves the sensitivity of the system. In the case of the field strength measurements, increasing the bandwidth lowers the sensitivity since at the low signal to noise ratios encountered (i.e. less than 10 dB), the effects of multiplicative noise overwhelm the improvement in the processing gain.

4.2 Frequency Range

The two main frequency dependent components in a CDF system are the antenna system, and the front end of the receiver section.

In the antenna system, two important factors that affect frequency response are dipole spacing and dipole length. The upper frequency response is limited mainly by dipole spacing, since the minimum distance between at least one pair of dipoles is restricted to being 0.4 wavelengths or less to avoid phase measurement errors. At lower frequencies the smaller spacing (relative to the wavelength) has the effect of reducing the accuracy of the system in the presence of internal noise (see Figure 21). Additionally the gain of the antenna decreases as the wavelength increases (provided the dipole length is less than one half a wavelength). Both of these effects cause a decrease in sensitivity as the frequency decreases, which ultimately limits the lower frequency response of the system.

The frequency limitations of the antenna array can be overcome by using different antenna arrays for different frequency bands. Typically, antenna arrays are stacked one above the other on the same antenna mast, starting with the largest antenna array at the bottom. For example, the Watkins-Johnson WJ-9871 pseudo-Doppler antenna system has a frequency range from 20-1000 MHz. It accomplishes this by using two arrays, one to cover the 20-235 MHz band, and one to cover the 150-1000 MHz band.

Except for the front end of the receiver, the rest of the CDF system is essentially frequency independent, since the RF signal has been down converted to a fixed IF frequency. The front end of the receiver is frequency limited by the components used, so several front ends may be used to handle the various frequency bands of interest.

Essentially the frequency limitations of CDF systems are user requirements, cost, and complexity, and not technology.

4.3 Accuracy

The accuracies of CDF systems are expressed (in degrees) as a range (e.g $\pm$2 degrees) or as a RMS value. Unless otherwise indicated, these values can assumed to be equivalent.

In reviewing the specifications for CDF systems, there are two different terms used to describe accuracy. This is a result of the fact that CDF systems make assumptions about the environment that are not always true (e.g. no multipath). As a result, it is difficult to predict the accuracy of these systems under all conditions. This has led to the use of two different terms to describe accuracy, namely, equipment accuracy, and operational accuracy.

4.3.1 Equipment Accuracy

The equipment accuracy (also called instrumental accuracy, or system accuracy) is a measure of the overall accuracy of all or most of the system under ideal environmental conditions (i.e. the assumptions made about the environment in Section 2.0 are true).

One method of measuring equipment accuracy is with the use of a bearing simulator. The bearing simulator injects correctly phased signals into the system, effectively bypassing the antenna system, to simulate an RF signal arriving from a known bearing. Comparing the measured bearing with the simulated bearing gives the bias error. Repeating this procedure at different frequencies (and possibly different simulated bearings) results in a set of bias errors. The equipment accuracy is the RMS value of this set.

Another method of measuring equipment accuracy places the CDF system on a turntable at a site with insignificant multipath or at least known characteristics (i.e. site effects can be corrected for afterwards). A signal from a known direction is transmitted to the CDF system and the bearing angle is measured. After accounting for the offset introduced by the turntable, the bias error is computed by comparing the measured bearing to the actual signal bearing. By repeating this procedure for a number of different turntable orientations and frequencies, a whole set of bias errors is generated. As in the first method, the equipment accuracy is the RMS value of the set of bias errors.

A disadvantage of the first method is that it does not account for errors resulting from the antenna system which can be significant. Additionally, the results may only be valid for a single bearing. Consequently, the results tend to be extremely good (e.g. see the PA 555 in Table 1).

The second method does account for the antenna system, but still has limitations. Normally, the site used to test the accuracy of the system is the same site used to calibrate the system, so the equipment accuracy results are generally reasonably good (e.g. see CELS in Table 1). Unfortunately, since it is difficult to find a site truly free of multipath effects, or a least be able to account for them, errors can be incorporated into the system calibration table which are a function of the site and not the equipment.

4.3.2 Operational Accuracy

The operational accuracy of a CDF system is a measure of the overall accuracy in a realistic signal environment. However, since it is difficult to define what a realistic environment is, operational accuracy is rarely listed in specifications.

In tests on CDF systems, operational accuracy has been found to be a function of the environmental conditions, rather than equipment accuracy. For example, tests carried out at DREO on the Watkins-Johnson WJ-9871 single channel pseudo-Doppler system showed the equipment accuracy (including antenna system) to be better than 2 degrees at 56.5 MHz and 62.5 MHz. The operational accuracy of the system at various sites, however, was found to range from 3 to 9 degrees. As a point of interest, this system is specified to have an operational accuracy of 3 degrees.

When specified, operational accuracy is based on the manufacturers interpretation of a realistic environment, which is often more optimistic than realistic!. Since the interpretation may vary from manufacturer to manufacturer, a comparison of different systems based on this specification would be meaningless.

4.4 Minimum Signal Duration

The minimum signal duration specification provides information on how long a signal must remain on air before its bearing angle can be measured. This is important when considering the performance of a CDF system against short duration signals such as burst or on/off type signals.

One disadvantage of noise filtering is the limitation it places on the response time of the CDF system when intercepting short duration signals that are transmitted for a period of time less than twice the integration time constant. Integration of the input information when the signal is absent increases the amount of noise energy in the the measurement without increasing the signal energy. This results in a decrease in accuracy.

An example of the results of this effect in a phase interferometer system are shown in the upper curve of Figure 23. In this case, random bearing errors are caused by internal noise. For short duration signals, when the signal is off, the RMS error is so large (103.92 degrees) that it tends to completely dominate the overall error unless the on time of the signal is very nearly twice the integration time constant.

A second disadvantage is that even if the signal duration is just long enough, it is unlikely that the operator would be able to pick out a single good measurement from a series of random measurements.

The solution used in some CDF systems to solve both these problems is to make measurements and update the bearing display only when a signal is present. The presence of the signal is determined by comparing the input signal power to an operator selected threshhold value. For the example, this results in the accuracy given by the lower curve in Figure 23. For different signal to noise ratios, bandwidths, etc. The results would be expected to vary as discussed in Section 3.8.

From the above discussion it is apparent that the minimum signal duration specification may be as simple as twice the value of the minimum integration time constant setting. However, if "signal only" integration is a feature of the CDF system, then the signal to noise ratio, input bandwidth, and the minimum acceptable error must also be specified before meaningful comparisons can be made between various CDF systems.

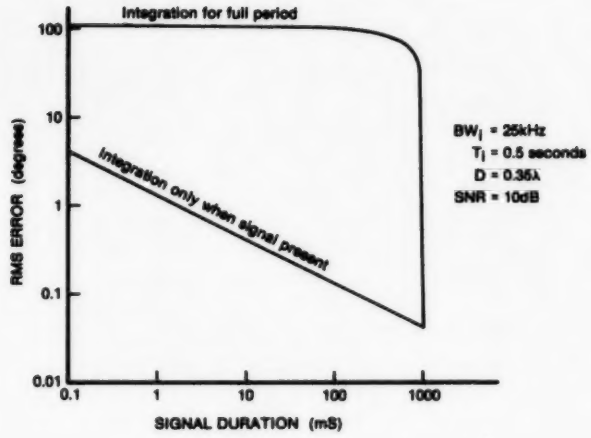


FIGURE 23: CDF System Response to Short Duration Signals

5.0 SUMMARY AND CONCLUSIONS

This report discusses several different types of conventional land based VHF/UHF tactical direction finding systems (called CDF systems in this report). These systems fall into three different categories: Watson-Watt, pseudo-Doppler, and phase interferometer.

The Watson-Watt system works by measuring the magnitude of the signal vector along two orthogonal axes. These quantities are then used as arguments of the arc tangent function to compute the signal bearing. Measurements of the signal components are made using orthogonal Adcock antenna arrays.

The pseudo-Doppler system sequentially samples a circular array of dipole antennas. The sequential sampling modulates the signal in frequency, and the phase of the modulation waveform with respect to the antenna timing sequence is used to determine the signal bearing.

The phase interferometer system uses the phase difference information from a number of spatially separated dipole antennas to compute signal bearing.

Several variations of these systems exist which share the same operating principles, but differ in implementation. The most common among these limit the number of receivers required to one or two. Although this reduces the hardware requirements, it usually increases the complexity of the system. Additionally, where time sampling methods are used to restrict the number of receivers (e.g. single channel pseudo-Doppler), the response time of the system is also increased.

In a comparison of these systems, the phase interferometer system is theoretically the best system. It is slightly more accurate than the Watson-Watt system in the presence of multipath, co-channel interference and external noise sources for similar antenna diameters, and can be made even more accurate by increasing the diameter beyond one half of a wavelength. The phase interferometer also has a faster response time than the pseudo-Doppler system since, in the pseudo-Doppler system, antenna outputs are sampled sequentially rather than simultaneously. In practice, the the expense and difficulty of building the hardware required to realize the full potential of the phase interferometer may negate it's advantages.

Bearing measurement errors caused by co-channel interference, polarization, signal elevation angle, modulation, noise, and equipment errors are all discussed. Techniques such as averaging of measured quantities with respect to time, equipment calibration, and careful attention to equipment design and construction are all methods that can be used in combination to reduce the resultant errors to acceptable levels (less than a degree).

Multipath is also discussed. It is the most serious problem since averaging measurements over time will not reduce the resulting bias errors in the bearing measurements. Although calibration could be used to improve accuracy in the presence of multipath, it must be performed for each new site - not very practical for a mobile system. Wide aperture systems also offer some improvement in accuracy, but only when the diameter exceeds one half a wavelength (in most cases CDF system diameters are smaller than this for the purpose of mobility).

The difficulty in dealing with multipath appears to be the main stumbling block in building CDF systems with accuracies of 0.1 degrees. The operational accuracies of the best CDF systems are, in fact, on the order of several degrees.

The manufacturer supplied specifications for CDF systems are also discussed, specifically, sensitivity, frequency range, accuracy, and minimum signal duration. With the exception of frequency range, most of these specifications were found to omit relevant information pertaining to how the specifications were obtained. As a result, it is difficult to make any meaninful comparison between the performance of commercial CDF based on their specifications.

TABLE 1: SPECIFICATIONS FOR COMMERCIAL CDF SYSTEMS

Rohde and Schwarz PA2000 [22]
- Operating Principle..... 3 channel Watson-Watt
- Sensitivity..... 2-20 uV/m for 2 degree RMS error and a 6 kHz bandwidth
- Frequency Range..... 2-512 MHz
- Equipment Accuracy..... 1 degree RMS
- Operational Accuracy..... (not given)
- Minimum Signal Duration... 1 mS

Watkins-Johnson WJ-8975A [23]
- Operating Principle..... single channel pseudo-Doppler
- Sensitivity..... 10 dB SNR for ±3 degree error
- Frequency Range..... 20-500 MHz
- Equipment Accuracy..... 1 degree RMS
- Operational Accuracy..... 3 degrees RMS
- Minimum Signal Duration... (not given)

Rohde and Schwarz PA555 [24]
- Operating Principle..... differential pseudo-Doppler
- Sensitivity..... 3-10 uV/m for ±2 degree error
- Frequency Range..... 20-1000 MHz
- Equipment Accuracy..... ±1 degree
- Operational Accuracy..... (not given)
- Minimum Signal Duration... 10 ms

EM Systems E210 [25]
- Operating Principle..... single channel phase interfer.
- Sensitivity..... 0 dB SNR for 1 degree RMS error
- Frequency Range..... 20-500 MHz
- Equipment Accuracy..... 1 degree RMS
- Operational Accuracy..... (not given)
- Minimum Signal Duration... 150 ms

Thomson-CSF TRC296 [26]
- Operating Principle..... single channel phase interfer.
- Sensitivity..... 0.8-10 uV/m for 2 deg. RMS error
- Frequency Range..... 20-1350 MHz
- Equipment Accuracy..... 1 degree RMS
- Operational Accuracy..... (not given)
- Minimum Signal Duration... 100 mS

ESL AN/MRD-501 (CELS) [27]
- Operating Principle..... single channel phase interfer. with delay lines
- Sensitivity..... -110 dBm for 1 degree RMS error at a bandwidth of 8 kHz
- Frequency Range..... 20-150 MHz
- Instrumental Accuracy..... 2 degrees RMS
- Operational Accuracy..... (not given)
- Minimum Signal Duration... (not given)

TABLE 1: SPECIFICATIONS FOR COMMERCIAL CDF SYSTEMS (cont)

Watkins-Johnson WJ-8976 [28]

Operating Principle.....	three channel phase interfer.
Sensitivity.....	(not given)
Frequency Range.....	2-500 MHz
Equipment Accuracy.....	2 degrees RMS
Operational Accuracy.....	(not given)
Minimum Signal Duration...	10 μS

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